ANNUAL RESEARCH REPORT
U.S. WATER CONSERVATION LABORATORY

1994

USDA - AGRICULTURAL RESEARCH SERVICE
Phoenix, Arizona

ANNUAL RESEARCH REPORT

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U.S. WATER CONSERVATION LABORATORY
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INTRODUCTION

The U. S. Water Conservation Laboratory (USWCL) Annual Research Report is intended to describe progress on our research projects in 1994 and plans for 1995 and beyond, for upper level management within the Agricultural Research Service, other ARS research locations involved in natural resources research, and our many collaborators and cooperators. It is our intent to keep the individual reports short but informative, focusing on what is being done and why, the problem, objectives, approach, brief results (what it all means), future plans, and cooperators. We want to make sure that the product of the research and its contribution to water conservation are clear to all.

This Research Report, our Annual Program Review and Planning Meeting held each year in January, and the Long-Range Plan for the USWCL (completed in October 1994 as part of a Pacific West Area planning process) all provide opportunities for us to tell our research story and to assess where we are in our programs by looking at the long-range goals and expected outcomes, strategies for getting there, and resources needed. If you are interested, we would be pleased to share the Long-Range Plan for the USWCL with you and/or to invite you to next year's Annual Program Review and Planning Meeting--just let us know.

Late in FY94, additional permanent funding was directed to the USWCL to increase research on the application of technology to improve irrigated agricultural performance within the Irrigation Group and on utilizing remotely sensed data to aid farm management within the Remote Sensing Group. The increased funding and retirements of Drs. Jackson (Remote Sensing) in January 1993 and Thompson (New Crops) in April 1994 has/will allow some scientific staff increases during FY95. Dr. Terry A. Coffelt, Geneticist, came to the USWCL from the Peanut Production, Disease and Harvesting Research Unit at Suffolk, Virginia, in November 1994, and will work with New Crops. We are currently advertising for an Agronomist/Agricultural Manager to join the Remote Sensing Group.

As a policy, we strive to leverage our available base funding into well-targeted, broader-based programs by attracting outside resources. We are committed to working collaboratively with other agencies and industry in bringing post doctorates, visiting scientists and engineers, graduate students, and persons on sabbaticals to the USWCL to maintain or expand our research programs.

Outside resources are instrumental in our continued work in major program areas. In-kind human resources provided by many of our cooperators and collaborators are highly significant and enhance our programs, especially by each individual's stimulating effects on our research efforts (please refer to the list of Cooperators shown at the end of each report). A number of organizations are contributing significant financial support to the USWCL during FY95 as follows: The Irrigation Group is receiving outside support through the USDA Office for International Cooperation and Development for a three-year collaborative study, which began in 1992, with the National Agricultural Research Project (NARP) in Egypt dealing with the effects of land leveling precision and tillage practices on surface irrigation performance; and from the Arizona Department of Water Resources, Phoenix Active Management Area, to develop software for improving the design and management of sloping border irrigation systems. The Department of Energy is supporting the CO_2-Climate Change Group program to evaluate the interactive effects of elevated CO_2 and increased temperature on plant growth and physiological processes, including the development of predictive models. Additionally, temporary ARS Global Change funds help support the free-air CO_2 enrichment (FACE) project. The New Crops Group will receive support through the USDA Alternative Agricultural Research and Commercialization Center for commercialization of Lesquerella and for two programs supported jointly by DOD and the USDA/CSRS Office of Agricultural Materials: one, a two-year program to accelerate commercialization of vernonia, and the other to expand work on the extraction, characterization, and fabrication of guayule latex products for nonallergenic applications. The USDA-ARS National Germplasm Laboratory is supporting the collection of Lesquerella germplasm. Some funds from the terminated Cuphea germplasm program at Ames, Iowa, in FY94, have been transferred to the New Crops Group. In addition, the University of Arizona has been awarded two grants: one from the Department of Energy to continue the FACE Project, and the other from NASA to support students and travel for research in hydrologic applications of remote sensing. USWCL personnel are major collaborators in both. To the USWCL overall, this outside funding represents about 12% of our total budget for FY95, but it amounts to about 45% of our discretionary dollars. We thank these many cooperators/collaborators and will continue working to make these associations mutually beneficial in serving agriculture.

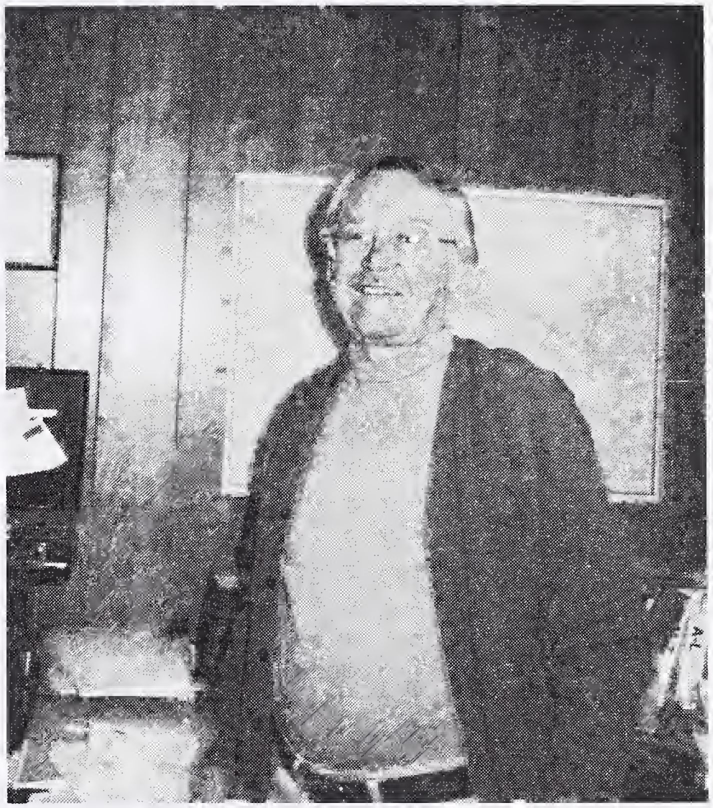
As always, we invite you to use this Annual Research Report. Let us know if there are questions or comments; all are invited and will be appreciated.

Allen R. Dedrick, Director

DEDICATION

Anson E. Tommy) Thompson, Research Geneticist, now Collaborator, at the U. S. Water Conservation Laboratory retired in May 1994. This report is dedicated to Tommy for his impact on developing the New Crops Program at the U. S. Water Conservation Laboratory (USWCL) and for his overall contribution to the science of horticulture.

Tommy is a Fellow of the American Society for Horticultural Sciences and the American Association for the Advancement of Science. In 1965 he received the Charles G. Woodbury Award in Raw Products Research and in 1966 the Asgrow Award in Vegetable Crops from the American Society for Horticultural Sciences. The Association for the Advancement of Industrial Crops recently changed an "Emeritus Award" to the "Anson E. Thompson Career Achievement Award." Tommy was the first recipient of the Thompson award, which was presented at a symposium held in New Orleans in his honor.



Anson E. (Tommy) Thompson

Tommy received practical experience on his family's farm where he grew up in Oregon. He received a B.S. in Horticulture from Oregon State University in 1948 and a Ph.D. in Plant Breeding from Cornell University in 1952. Prior to working for ARS, Tommy had a long academic career. He spent 20 years at the University of Illinois in various capacities, including Professor of Genetics, Assistant Director of the Experiment Station, and Division Head of Vegetable Crops. During this time he and his family spent two years in India as part of the University of Illinois/USAID Contract Team. Tommy served as Professor and Head of the Department of Horticulture and Landscape Architecture at The University of Arizona, Tucson, for five years. He also led a team of scientists for three years for the Rockefeller Foundation in Indonesia working on winged beans production and tomato quality for that region. Tommy joined the USDA's Agricultural Research Service in 1979 as a Program Leader for Vegetable, Florist, and Nursery Crops; and Program Coordinator for Tropical and Subtropical Agricultural Research, National Program Staff, Beltsville, Maryland. In 1983 he moved to the USWCL to begin the New Crops Program.

Tommy's work on New Crops has been internationally recognized and respected. He served as the first president of the Association for the Advancement of Industrial Crops, which he was instrumental in forming. He initiated and led research on development of Cuphea, Lesquerella, Guayule, and Vernonia as potential new industrial crops. As a result of his successful research, industry envisions full commercialization of Lesquerella within four to six years with continued R&D. He is author or coauthor of over 100 publications covering a wide range of topics. He has been a national and international leader in research of new crops; vegetable breeding and genetics; tropical agriculture; research administration, coordination, and program planning; and programs in developing countries.

We at the USWCL know and respect him as a human being and as a coworker. Warmest personal regards, Tommy.

U. S. WATER CONSERVATION LABORATORY ORGANIZATIONAL DESCRIPTION AND MISSION STATEMENTS

The overall mission of the U. S. Water Conservation Laboratory (USWCL) is to conserve water and protect water quality in systems involving soil, aquifers, plants, and the atmosphere. Research thrusts involve developing more efficient irrigation systems, improving the management of irrigation systems, developing better methods for scheduling irrigations, developing the use of remote sensing techniques and technology, protecting groundwater from agricultural chemicals, commercializing new industrial crops, and predicting the effect of future increases of atmospheric CO_2 on climate and yields and water requirements of agricultural crops.

The U. S. Water Conservation Laboratory research program is organized under two Research Units: Irrigation and Water Quality (I&WQ) and Environmental and Plant Dynamics (E&PD). I & WQ focuses on water management with emphasis on irrigation and water quality; E & PD concentrates on carbon dioxide-climate change, germplasm development for new crops, and remote sensing. Drs. Albert J. Clemmens and Bruce A. Kimball are the Research Leaders for the respective Research Units. The organizational structure for the USWCL is shown as Figure 1; and the entire USWCL personnel list in Table 1.

The mission of the Irrigation and Water Quality Research Unit is 1) to develop management strategies and tools for the effective use of water and fertilizers in irrigated agriculture, 2) to develop tools for the protection of groundwater supplies from degradation as the result of agricultural and urban waste management practices, and 3) to transfer these results to practice through technology transfer efforts. The research unit takes a holistic approach to resolving water management problems within irrigation projects through research aimed at both farm and project operations and management and their interactions. Thus the focus is on identifying individual actions and practices that can have a positive effect on water quality and quantity overall. The unit also focuses on methods for resolving water supply and quality issues on a larger scale.

The broad mission of the Environmental and Plant Dynamics Research Unit is to develop optimum resource management strategies for meeting national agricultural product requirements within the context of possible changes in the global environment. Specifically, the Unit seeks: (a) to develop new methods for assessing water and carbon dioxide fluxes in the soil-plant-atmosphere system, to quantify plant stress and its effect on crop yield, and to predict the effects of increasing carbon dioxide and climate change on plant growth and water use; (b) to develop suitable new and alternative crops capable of meeting national needs for renewable, agriculturally-based industrial products; and (c) to develop remote sensing and related tools for use in water conservation, irrigation scheduling, drought prediction and avoidance, and for monitoring crop conditions and assessing environmental change. All aspects of the program are designed to meet the challenges and opportunities imposed by dynamic environments, particularly those stressful to plants and their possible effects on crop production. A common thread uniting these efforts is the overall theme of increasing plant water use efficiency and conserving and improving the quality of agricultural water supplies. To attain these ends, the Unit is organized into a closely knit, multidisciplinary research group whose underlying philosophy is to devise multifaceted approaches to solving critical problems associated with the phenomenon of global environmental change.

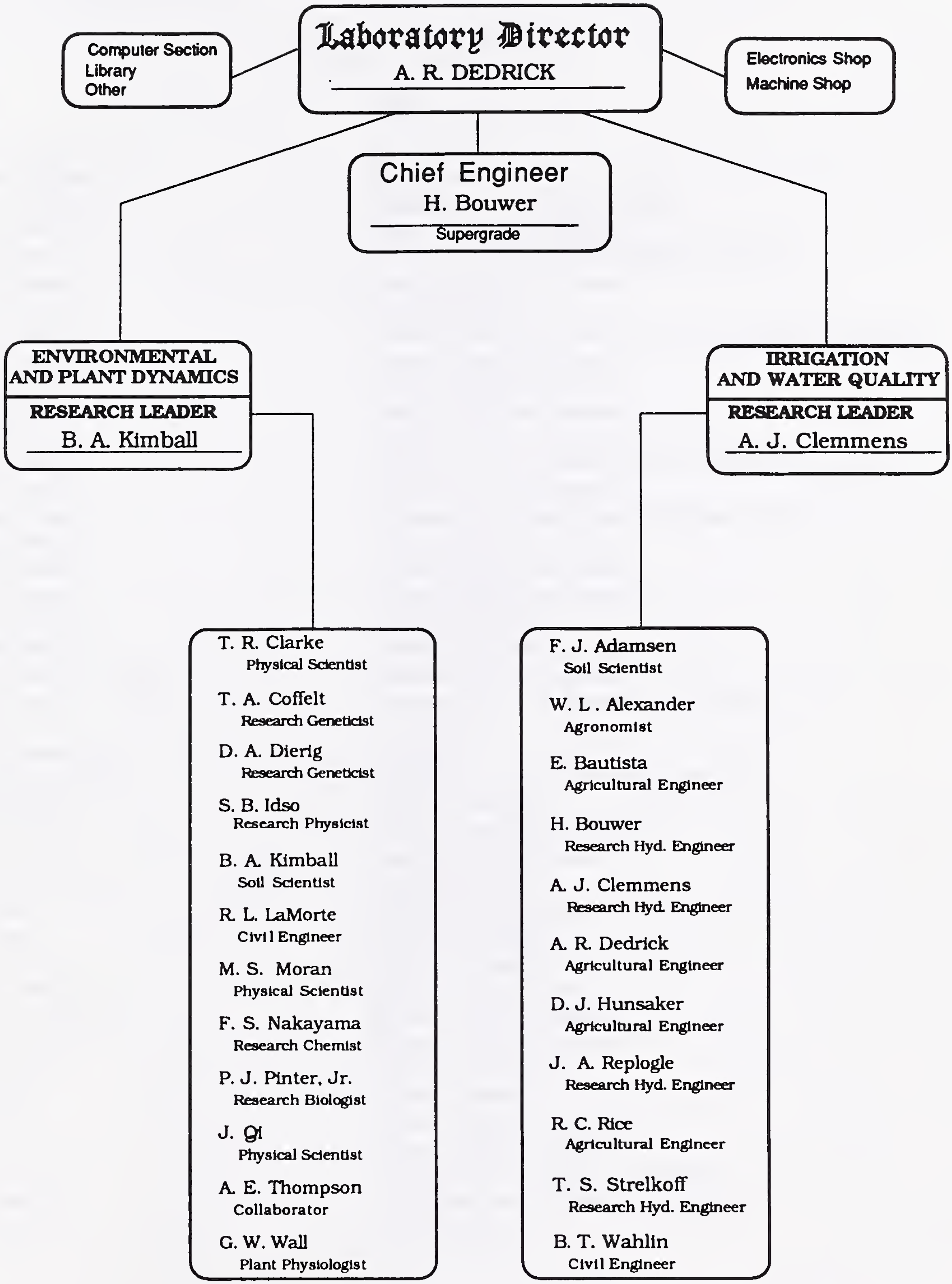


Figure 1. U. S. Water Conservation Laboratory Organization, December 31, 1994

Table 1. U. S. Water Conservation Laboratory Staff, December 31, 1994

PERMANENT EMPLOYEES

Name	Title
Adamsen, Floyd J.	Soil Scientist
Alexander, William L.	Agronomist
Arterberry, Carl A.	Agricultural Research Technician
Auer, Gladys C.	Physical Science Technician
Bailey, Benita L.	Secretary (Office Automation)(Retired 7/29/94)
Bouwer, Herman	Research Hydraulic Engineer
Clarke, Thomas R.	Physical Scientist
Clemmens, Albert J.	Research Leader and Supervisory Research Hydraulic Engineer
Coffelt, Terry A.	Research Geneticist (Plants)
Coleman, David L.	Physical Science Technician
Corris, Virginia D.	Office Automation Assistant
Dahlquist, Gail H.	Agricultural Science Research Technician
Dedrick, Allen R.	Laboratory Director and Supervisory Agricultural Engineer
Dierig, David A.	Research Geneticist (Plants)
Eastman, Lynnette	Biological Technician (Plants) (Resigned 11/4/94)
Gerard, Robert J.	Laboratory Support Worker
Harner, Paulina A.	Secretary (Office Automation)
Heckart, Donna J.	Secretary (Office Automation)
Hunsaker, Douglas J.	Agricultural Engineer
Idso, Sherwood B.	Research Physicist
Johnson, Stephanie M.	Biological Science Technician
Kimball, Bruce A.	Research Leader and Supervisory Soil Scientist
LaMorte, Robert L.	Civil Engineer
Lewis, Clarence L.	Machinist
Martinez, Juan M. R.	Agricultural Science Research Technician
Mastin, Harold L.	Computer Assistant
Mills, Terry A.	Computer Programmer Analyst
Moran, M. Susan	Research Physical Scientist
Nakayama, Francis S.	Research Chemist
Padilla, John	Engineering Technician
Pettit, Dean E.	Electronics Engineer
Pinter, Paul J., Jr.	Research Biologist
Powers, Donald E.	Physical Science Technician
Rasnick, Barbara A.	Physical Science Technician
Replogle, John A.	Research Hydraulic Engineer
Rice, Robert C.	Agricultural Engineer
Rish, Shirley A.	Program Analyst
Rokey, Ric	Biological Science Technician
Salisbury, T. Lou	Secretary Office Automation
Seay, L. Susan	Publications Clerk (Office Automation)
Seay, Ronald S.	Agricultural Science Research Technician
Wall, Gerard W.	Plant Physiologist

TEMPORARY EMPLOYEES

Name	Title
Arnold, Stacy	Biological Science Aide
Baker, Michael	Research Assistant
Bautista, Eduardo	Agricultural Engineer
Bhattacharya, N.	Collaborator
Colbert, Sharette	Physical Science Technician
Fritz, Kent I.	Physical Science Aide
Gallagher, Daniel	Physical Science Technician
Garcia, Richard	Plant Physiologist (Resigned 6/24/94)
Gulbranson, Scott	Biological Science Lab. Technican
Holifield, Chandra	Physical Science Aide
Johnson, David	Engineer
Kuramoto, Jane	Physical Science Techncian
Mitchell, Tom	Engineering Technician
Perry, Edward	Biological Science Technician
Qi, Jiaguo	Physical Scientist
Rebman, Jon	Biological Science Technician
Thompson, Anson	Collaborator
Tomasi, Belinda	Biological Science Lab. Aide
Wahlin, Brian	Civil Engineer
West, Kathy	Laboratory Science Aide
Yanas, Ruben	Engineering Aide

TEMPORARY STATE EMPLOYEES

Brooks, Talbot	Research Technician
Colaizzi, Paul	Research Assistant
Denaro, John	Research Technician *
Freitag, Laurel	General Maintenance Mechanic
Gerle, Michael	Research Technician *
Husemann, Kevin	Biological Science Aide *
Leake, Gregory	Research Technician
Lemke, Kellie	Word Processor Operator *
O'brien, Carrie	Biological Aide
Oliveri, Laura	Biological Science Technician
Oliveri, Jose	Research Laboratory Assistant
Shaw, Mary	Biological Science Aide *
Sherrill, William	Biological Science Aide *
Smith, Leslie	Research Technician *
Strand, Robert J.	Engineering Aide
Strelkoff, Theodor	Research Hydraulic Engineer
Tomasi, Pernell	Research Aide
Villalobos, Miguel	Research Assistant *
von Schmidt, Baran	Computer Programmer Assistant

* Research Support Agreement (RSA) appointment termination

Number of USWCL Scientists that Visited other Countries in 1994

Number of Foreign Scientists Visiting USWCL in 1994

More than 5 | 5 | 4 | 3 | 2 | 1

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INTEGRATED IRRIGATION SYSTEM WATER MANAGEMENT

MANAGEMENT IMPROVEMENT PROGRAM (MIP) FOR IRRIGATED AGRICULTURE

A.R. Dedrick, Supervisory Agricultural Engineer; E. Bautista, Agricultural Engineer;
S.A. Rish, Program Analyst; and A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Enhanced long-term management of water and other natural resources, grower profitability, and overall social well-being are essential to a sustainable irrigated agriculture. Because approaches to these objectives are often uncoordinated, all agricultural stakeholders--farmers, irrigation districts, other support and regulatory organizations, and other interested parties--need to interact proactively to address these needs. To this end, the Management Improvement Program (see figure 1 for an elaboration of the three-phased MIP process), a management process similar to those used to improve the performance of corporate organizations, was applied to the business of irrigated agriculture. The purposes of this research are 1) to develop, apply, and refine for future use the MIP methodology; and 2) to establish conditions in the MIP application area for the continued improvement of farming practices and support services provided to farms by district and other irrigation related agencies while conserving related resources.

APPROACH: In December 1990, under the direction of the U. S. Water Conservation Laboratory, an Interagency Management Improvement Program (IMIP) was initiated by seven agencies (see table in 1993 "Annual Research Report") interested in the potential of the MIP to support improved irrigated agricultural productivity, profitability, and natural resource management. From April 1991 to January 1994, a demonstration project was carried out in the Maricopa-Stanfield Irrigation and Drainage District (MSIDD) in central Arizona (see figure 2 for a schematic representation of participating entities). Following are milestones in the MSIDD-Area MIP during 1994 (see "Annual Research Reports," 1991 through 1993, for milestones during those years):
1)<u>Transition from the Formal, MIP Team-Assisted[1] Demonstration to the Ongoing MIP in the MSIDD Area (1/94)</u>. From the inception of the Demonstration MIP, institutionalization of the MIP's approach to program development and delivery was considered essential. In response, establishment of the local, grower-led MSIDD MIP Coordinating Group (CG), consisting of five growers and representatives of seven agencies (see table in 1993 "Annual Research Report") was initiated during the Management Planning Phase. In January 1994, a special closure meeting, chaired by the now operational CG, marked the end of formal leadership of the Demonstration MIP by the MIP Team and assumption by the CG of ongoing responsibility to initiate and guide future MIP initiatives in the MSIDD area. Meeting participants included area growers, MSIDD staff and board members, and representatives from agencies that were involved in or had originally mandated the Demonstration MIP. A review of the Demonstration MIP's progress and status was presented, initial evaluation findings were reported, and input for continuing and expanding MIP activities was solicited.
2)<u>Completion of the MSIDD-Area MIP Evaluation and Report (10/94)</u>. A formal evaluation of the MSIDD-Area MIP was completed and the report published in October 1994. The evaluation was conducted by a three-member team comprised of an outside consultant experienced in organizational change processes as team leader and two MIP Team members to provide historical experience from the demonstration project.[2] The evaluation focused on 1) the degree to which the Demonstration MIP accomplished its intended results within the MSIDD area, i.e., advancing understanding and improving communication and coordination among agencies and with growers and identifying improvement opportunities with the potential to improve grower profitability, sustainability, and natural resource management; and 2) how the learnings from the Demonstration MIP might guide the next steps of MIP model development and subsequent applications.
3)<u>Sharing of Evaluation Findings (11/94 and 12/94)</u>. Following publication of the Evaluation Report, the MIP Team held separate meetings with participating agencies most central to ongoing MIP programs in the MSIDD area and/or

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[1] The MIP Team includes Dedrick, Bautista, and Rish of the USWCL; and consultants W. Clyma (MIP Specialist) and D. B. Levine (Management/Team-Building Specialist). The MIP Team provided overall management of the demonstration activities, which included the direct development and facilitation of MIP events. In addition, the Team maintained ongoing communication with participants, addressed concerns and problems as they arose, and was responsible for the development and publication of MIP-related documents.

[2] Evaluation Team members were W. E. LeClere, organizational development specialist, team leader; and E. Bautista and S. A. Rish, agricultural engineer and program analyst, respectively, from the USWCL.

to future applications of the model: the MSIDD Board of Directors, MSIDD Management Staff, MSIDD-Area MIP CG, U. S. Bureau of Reclamation (USBR), Natural Resources Conservation Service (NRCS, formerly Soil Conservation Service), and Arizona Department of Water Resources (ADWR). The purpose of the meetings was to review evaluation results, including key impacts of the Demonstration MIP, and to consider how the respective organizations could use the evaluation findings, both inter- and intraorganizationally, to benefit from continuing application of the MIP methodology.

FINDINGS: The Evaluation Report concluded, "To a remarkable degree, the Demonstration MIP achieved its stated purposes. Interviewed agency participants, growers, and mandators were virtually unanimous that...the MIP was successful and worthwhile." In the MSIDD area, the MIP advanced a common understanding of the area's irrigated agriculture, identified improvement opportunities, and improved communications and coordination among agencies and growers. Findings also revealed that MIP programs resulted in technology transfer and improved resource management, both expected to continue as additional programs are implemented and reach increasing numbers of growers. Monthly CG meetings during 1994 continued to address institutional development and the initiation and oversight of interorganizational programs. Town Halls, a quarterly newsletter, and grower-to-grower meetings are receiving favorable reports; grower involvement is being expanded; efforts to develop feasible farm-specific assistance continue; and spin-off activities are being initiated by CG members. Learnings have spread beyond the District as MIP participants interact with growers outside MSIDD's service area. Post-evaluation meetings reaffirmed evaluation findings about MIP accomplishments and identified opportunities for initiating and supporting interagency activities as well as ways in which the MIP methodology could be used by the respective organizations to further their own missions. In addition to addressing how well the Demonstration MIP accomplished its intended purposes in the MSIDD area, the evaluation findings also were used to develop nine recommendations to guide future applications.

INTERPRETATION: Strengths of the MIP model include the capacity of its three phases, separately and together, to achieve impact by fostering and/or building on such characteristics as a continuing commitment of participants during an extended process; grower receptiveness to learning and change; and open, candid communication among agencies and growers. Areas identified for strengthening the model include appropriately involving key stakeholders in the initial positioning of an application; gaining clear mandates from key agencies; maintaining appropriate expectations among agencies and growers based on an understanding of what the MIP is intended to accomplish and the time and resources involved; and at the outset, developing a framework for the application's assessment. In the post-evaluation organizational meetings, attendees' responses to a start-up question asking them to relate something about the MIP that exceeded their expectations were decisive and positive (see table 1 for a summary of responses). A consistent message conveyed in the meetings was that there had been a change in "the way people do business" based on an understanding of the irrigated agricultural system and of mission, issues, and needs among growers and organizations. Attendees also indicated a clear recognition that understanding and communication are the essential foundation of sustainable positive change and that obtaining them requires a substantial investment of time and resources. Further, it was suggested that impacts achieved in the MSIDD area are "the tip of the iceberg," with the expectation that future efforts will identify significant additional opportunities.

FUTURE PLANS: Work will focus on 1) publications documenting the Demonstration MIP, including a special issue of *Irrigation and Drainage Systems Journal*, 2) a manual to guide future MIP applications, and 3) exploration of appropriate reapplication of the MIP model. Although the MIP successfully accomplished change and identified further opportunities in the MSIDD area, the principal criterion for future use of the process will be the need to address an identified problem (i.e., a problem-driven situation). Leadership of the next application (or applications, which may prove more advantageous) is seen as transitional, from USWCL in a hands-on role to one of training and guidance. Appropriate institutionalization of the refined MIP methodology outside of ARS will continue to be explored.

COOPERATORS: Cooperators include entities listed in figure 2, as well as Colorado State University. Funding has been provided by ARS, USBR, NRCS, and ADWR; with significant in-kind contributions by all involved.

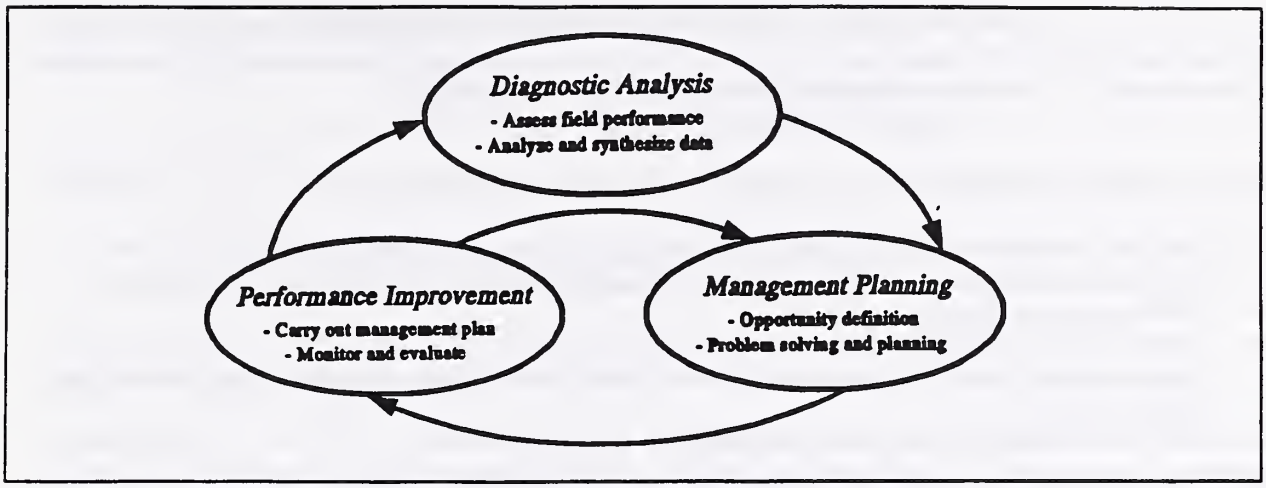
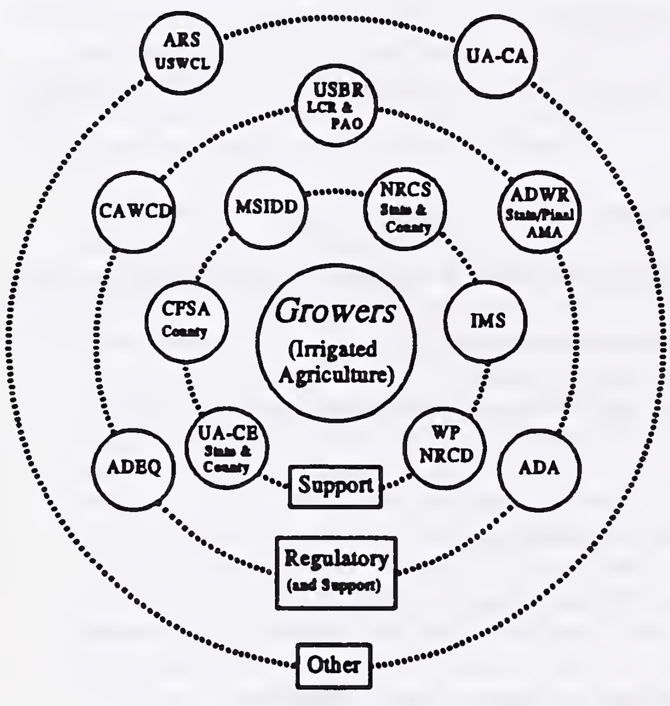


Figure 1. The three phases of the Management Improvement Program feed into one another. Diagnostic Analysis yields an interdisciplinary understanding of the performance of irrigated agriculture in the area. Management Planning results in a shared understanding of the performance among growers and participating organizations as well as identification of opportunities for improvement and jointly developed plans for managerial and technological changes to address those opportunities. Performance Improvement results in implementation of the plans and establishment of long-term, self-supporting mechanisms to sustain the effort after the formal end of the MIP.



ADA - Arizona Department of Agriculture
ADEQ - Arizona Department of Environmental Quality
ADWR - Arizona Department of Water Resources
AMA - Active Management Area
ARS - Agricultural Research Service, U. S. Water Conservation Laboratory
CFSA - Consolidated Farm Service Agency
CAWCD - Central Arizona Water Conservation District
IMS - Irrigation Management Service
MSIDD - Maricopa-Stanfield Irrigation & Drainage District
NRCS - Natural Resource Conservation Service
UA-CA - University of Arizona College of Agriculture
UA-CE - University of Arizona Cooperative Extension
USBR - U. S. Bureau of Reclamation
LCR - Lower Colorado Region
PAO - Phoenix Area Office
WPNRCD - West Pinal Natural Resource Conservation District

Figure 2. Schematic representation of entities involved in irrigated agriculture in the MSIDD-Area. Entities were included as participants because of their potential to impact irrigated agriculture in the area. Improved profitability and sustainability of irrigated agriculture (along with improved natural resource management) were the goals of the Demonstration MIP; therefore, growers, the main focus of the program, are shown appropriately in the center. Moving outward from the growers, the first circle connects organizations or entities directly supporting agriculture in the MSIDD area; the second connects organizations with primarily regulatory missions although they may also have some support functions; and the furthest circle includes the two research and/or educational organizations involved.

Table 1. Summary of participant responses to the start-up question in the post-evaluation organizational meetings. Attendees were asked to share something they had seen, heard, or read about the Demonstration MIP that exceeded their expectations. A total of about 40 people participated in the six meetings.

The Overall Scope and Contribution of the Demonstration MIP in the MSIDD Area

- The MIP clearly has a continuing life in the forefront of solving our problems. (2)[1]
- The scope covered more than water delivery and District operations.
- MIP's success in getting folks together.
- The interagency planning process. (3)
- Cohesiveness of what's happening--MSIDD BOD, staff, growers all together as a single entity--seeing each other's problems. (2)
- The DA is invaluable information, a keystone.

General Impacts of the Demonstration MIP on Individuals and Agencies

- Changes in attitudes [by participants, agencies and growers], especially their expectations for the future, which now include participating with and for each other.
- Number of participants acknowledging significant personal change and learning.
- Change in agency-grower relationships--agencies take a greater personal interest in growers. (4)
- Information from growers led to insights that helped agencies understand themselves.
- Agencies' views of irrigated agriculture have changed.
- Regulatory agencies became more involved.
- Appears to be a change in the attitude of credit institutions--now see [MSIDD] as a stable, good district whose growers are a better investment.

Specific Impacts of the Demonstration MIP on the Irrigation District

- MSIDD is widely perceived as one of the best run districts, with things happening, folks working together, growers exchanging information.
- Perceived change from a top-down management to a growers' district.
- Specific technological changes recognized and made by MSIDD.
- MSIDD's shift in mission focus--from selling a product (water) to managing a resource. (2)
- MSIDD is still in business.

The Nature of Individual and Agency Involvement in the Demonstration MIP

- The degree of grower commitment and interaction with agencies and each other. (7)
- Amount and kind of interagency interaction. (5)
- Strength of support from MSIDD BOD. (4)
- MIP happened in spite of the financial constraints facing growers and the District.
- Meetings with large numbers of growers and agencies and the commonality among the people.
- Detail at which the MIP process was explored.

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[1] Numbers in ( ) indicate number of like comments consolidated.

IRRIGATION INDUSTRY/ARS COLLABORATIVE EFFORT[1]

A.R. Dedrick, Supervisory Agricultural Engineer; and
D. F. Heermann, Supervisory Agricultural Engineer

PROBLEM: The "Collaborative Effort," led by Dedrick and Heermann, was initiated in 1991. Its stated purpose,

> "for the Irrigation Industry and the Agricultural Research Service to foster and focus an ongoing partnership in support of irrigation that yields optimal societal benefit,"

centers on the need to "...foster and focus an ongoing partnership..." in sustaining an effort that can impact irrigation on a broad scale up through the national level.

APPROACH: In May 1991, a workshop with over 40 attendees, almost evenly divided between the Irrigation Industry and ARS irrigation and drainage researchers, met to launch the effort. At that meeting, a Leadership Group was mandated to lead the Collaborative Effort. Over the last three-and-a-half years, the Leadership Group has guided actions to address the agenda that emerged from the workshop, including meetings to adjust overall Collaborative Effort plans and to review and support its workgroup activities focused on three main thrusts:

- Supporting the Irrigation Association (IA) as a key representative of the Irrigation Industry in identifying priority irrigation related research needs and communicating them to the research community,
- Increasing the amount of collaborative research carried out by Irrigation Industry and ARS scientists and engineers, and
- Proposing and supporting a study by the Water and Science Technology Board (WSTB) of the National Academy of Sciences/National Research Council focusing on the future of irrigation in the United States.

FINDINGS: Key results of the Collaborative Effort over the last year include (see 1993 Annual Research Report for findings from the previous two-and-a-half years)

- Identification of Priority Research Needs. A Research Committee of the Irrigation Association, originally authorized by the IA's Board of Directors in 1992, was formally established in 1994. The committee met for the first time at the IA's Expo and Technical Conference in Atlanta under its recently appointed leadership, chaired by Mr. Richard J. Panowicz of Valmont Irrigation. The IA Divisions were represented at the meeting by the chairs and vice chairs. At that meeting, ARS National Program Leader Dale Bucks discussed ARS's response to the IA's initial list of Research Opportunities.[2] The ARS response provided feedback on irrigation and drainage research being conducted at 14 locations across the United States. The response focused on three categories: (1) current research that addresses IA research priorities, (2) expanded research during the next three years that will address IA research priorities, and (3) research that could be done during the next three years that was not listed in the IA research priorities, but was assessed to be applicable to industry needs. A number of ideas were discussed for further action by the committee: (1) get broader distribution of the "Yellow Pages" (the data base of ARS researchers in irrigation and drainage), (2) consider developing an expanded Yellow Pages-type data base that would include all irrigation and drainage researchers, (3) provide the information generated from the IA's research opportunities list and the ARS response to the IA legislative liaison, and (4) develop special technical sessions or workshops to be held at future IA Expo and Technical Conferences that would initiate discussion of special issues identified by IA as needing attention (e.g.,

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[1] Dedrick and Heermann (Irrigation and Drainage Research Unit, Ft. Collins, Colorado) have co-chaired the Collaborative Effort. Key input to the process has been provided by J. A. Chapman, Valmont Industries, Valley, Nebraska; L. E. Stetson, ARS, Lincoln, Nebraska; and S. A. Rish, ARS, Phoenix, Arizona, as Subgroup Co-Chairs; T. A. Howell, ARS, Bushland, Texas, for development of the "Yellow Pages"; and consultant D. B. Levine (Management/Team-Building Specialist) for overall facilitation of the Collaborative Effort.

[2] The list consisted of 32 items in 5 major "Research Opportunity" areas identified by the industry and was presented to ARS in September 1993.

improved sensors, reclaiming plastic used in irrigation systems). This first Research Committee meeting is viewed as the beginning of a longer-term process for conveying Irrigation Industry research needs to ARS and other research entities.

- Increasing the Amount of Collaborative Research Carried out by ARS and the Irrigation Industry. Activities in this area have focused on increasing the awareness of Irrigation Industry and ARS scientists and engineers about opportunities for collaborative research. Specific accomplishments during 1994 include continuation of the Collaborative Effort exhibit at the IA Expositions to gain visibility and provide information on collaborative research (1994 was the fourth exhibit). Support was again provided by IA and the ARS Offices of Technology Transfer, Interactive Cooperation, and Information. A one-hour session "IA/ARS Using Expertise to Expand R & D," an effort to provide information on collaborative research possibilities between ARS and the irrigation industry, was scheduled for Atlanta at the Expo but industry representatives did not respond to the session. Other approaches will be tried in the future. Again, news releases were provided on the Collaborative Effort.
- Proposing and Supporting the Water Science and Technology Board Irrigation Study. A study, "The Future of Irrigation in the Face of Competing Demands and Water Quality Constraints" was initiated in 1993 by the National Academy of Sciences, Water Science and Technology Board (WSTB). The idea for the study originated at the May 1991 workshop and subsequently was proposed to the WSTB. The study committee has met four times with their first meeting in October 1993. Dedrick has provided liaison between the Leadership Group and the Study Committee, having attended three of the four meetings. The study is funded by the Irrigation Association, USDA/ARS, USDI/Bureau of Reclamation, Ford Foundation, and Idaho Power Association, each of whom also provides a liaison to the process. The study report is scheduled for publication in late 1995.

INTERPRETATION: The enthusiastic willingness of representatives from both the Irrigation Industry and ARS to work toward the Collaborative Effort goals has proven fruitful. In discussions with industry representatives to the Collaborative Effort, they continue to note how the process has provided a successful experience in building ongoing interaction, understanding, and trust between a client group, in this case the Irrigation Industry, and ARS. The approach used with the Irrigation Industry has potential as a model for building partnerships between ARS and other client groups, especially as ARS moves toward more client involvement in our research program development and assessment (i.e., ARS's response to the Government Performance and Results Act).

FUTURE PLANS: As noted in the 1993 Annual Research Report, the Leadership Group last met in September 1993. Future efforts will include "seeing through" or maintaining activities already initiated. For the Priority Research Needs, continued input to IA likely will be required to assure institutionalizing of the Research Committee and to assure that ARS continues to provide appropriate follow-up to IA's identified research needs. For Increasing Collaborative Research, guidelines for continuation of the Collaborative Effort exhibit at the IA Expo will be developed, the exhibit at the Expo will be continued on an annual basis, and a workshop on collaborative research will be considered to introduce industry management and product engineers to CRADAs and other opportunities for collaboration with ARS. The liaison between the Collaborative Effort and the WSTB Study will be maintained. Future meetings of the Leadership Group, as well as adjustments of membership and focus, will depend on progress of the ongoing activities and the requirements of newly identified activities appropriate to the Collaborative Effort's goals.

COOPERATORS: Representatives of the Irrigation Industry and ARS were shown in the 1993 Annual Research Report.

HIGH-FREQUENCY, SMALL-VOLUME, LEVEL BASIN IRRIGATION FOR COTTON

D.J. Hunsaker, Agricultural Engineer; A.J. Clemmens, Supervisory Research Hydraulic Engineer; and W.L. Alexander, Agronomist

PROBLEM: Properly managed level basin irrigation systems designed to apply light, frequent water applications may increase cotton yields and reduce on-farm water use. In the Southwest, where cotton is a major crop, irrigation is accomplished predominantly with surface methods. Traditionally, surface irrigation systems are designed and managed to minimize irrigation frequency, resulting in a large volume of water applied during each irrigation. This approach tends to minimize labor and energy costs and allows the grower to maximize field lengths. However, irrigations scheduled at long intervals almost assures some degree of water stress during the growing season. Studies conducted in Arizona in recent years have demonstrated a significant yield advantage by increasing the frequency of water applications to cotton. The most critical period to avoid water stress and lint yield reduction is during peak fruiting according to some investigations.

In addition to potential yield benefits, ability to provide light applications could reduce water use requirements and decrease nutrient and fertilizer losses from excessive deep percolation. Irrigation purposes requiring light applications (e.g., seed germination, early season development, fertilizer applications, etc.) are often desirable but difficult to attain with surface systems designed to apply large volume irrigation. Typically, field conditions early in the season make over-application unavoidable.

Level basin irrigation is a viable surface irrigation method capable of attaining uniform and efficient applications of water, although extremely light applications (2 or 3 cm) are probably not feasible unless fields are excessively small. However, our experiences using farm-scale level basins (14 m by 250 m) in 1993 indicated light water applications of about 6 cm could be attained under high-frequency irrigation, particularly when furrows are smoothed and compacted.

The objectives of this research are to evaluate level basin design and management procedures for applying high-frequency, small-volume irrigation and to evaluate the economic feasibility of this irrigation approach for growing cotton in the southwestern United States.

APPROACH: High-frequency irrigation studies were conducted in 1994 on a 2-ha, precision-leveled, Mohall sandy loam field site at The University of Arizona, Maricopa Agricultural Center. After conventional cotton beds (1.0-m row spacing) were constructed, the field was separated into six borders separated by dikes. Each border/basin was 12 rows wide and 250 m long. Rectangular canal gates, installed at the head of each basin, controlled the irrigation water delivery from a concrete-lined open channel. The irrigation inflow rate delivered to the basins was measured in the open channel with a broad-crested weir located upstream from the basins. Furrows within each basin were interconnected at the tail end of the field.

The six basins were assigned to two irrigation managements: 1) low-frequency, large-volume irrigation (LF), and 2) high-frequency, small-volume irrigation (HF) during the peak fruiting period. Furrows within HF basins were smoothed and compacted using a weighted metal device shaped like a torpedo that was dragged through the field by a tractor during normal cultivation procedures in May and June. All basins were given approximately 190 mm of preplant irrigation in March, and a short staple cotton cultivar, Deltapine-20 (DP-20), was planted on April 15. Another early irrigation was given to all basins in early May, shortly after crop emergence.

Irrigation scheduling was based on the soil water balance method using AZSCHED, a computer model developed by the Agricultural and Biosystems Engineering Department, The University of Arizona. The model predicts the date and irrigation depth to be applied using weather data obtained from a nearby meteorological station for a specified management allowed depletion (MAD). LF basins were irrigated for a MAD level of 50-55% over the growing season. HF basins were scheduled the same as LF until peak fruiting (late June). During peak fruiting, HF basins were scheduled at 30-35% MAD.

Data collected included soil water content before and after irrigation; furrow intake rates prior to irrigation for adjacent wheel and nonwheel furrows at three locations in the basin; furrow advance times; infiltration opportunity times at several locations in the basins; surface water profiles during several irrigations; and cotton growth data. Final cotton yield was obtained by machine harvesting four central rows of each basin on October 5, 1994. Harvested yields were obtained in 13.7-m length increments over the entire length of row.

A companion field study on cotton yield response to high-frequency irrigation was carried out on a small adjacent field. DP-20 was planted on April 18, 1994, and grown under three irrigation regimes: 1) low-frequency (55%

MAD), 2) high-frequency (30% MAD), and 3) low-frequency (55% MAD) with high-frequency (30% MAD) during peak fruiting. All treatments received about the same amount of seasonal irrigation. Treatments were replicated six times in plots having eight rows of cotton, 10 m long. Two undisturbed cotton rows were machine harvested in all plots on 6 October.

FINDINGS: The target water requirement in table 1 was that calculated by AZSCHED for each of the level basin irrigations shown. The effects on furrow advance times (fig. 1) were evident following smoothing and compaction of the furrows for the HF management basins during the second irrigation in early June. There was a larger difference in advance between wheel (W) and nonwheel (N) furrows in the LF basins compared to the HF basins. Consequently, the ratio of the water requirement/gross application depth was much lower for the LF basins because of greater application volume required to complete the irrigation. There was less difference in the ratio between the two managements at mid-season. However, furrow advance for the high-frequency basins was quite rapid and uniform during mid-season compared to the LF (fig. 2).

Table 2 shows the average lint yields obtained for the irrigation managements in the level basins (a) and small plots (b). Some yield reduction may have occurred because of whitefly and other insect damage. In the level basins, yield under HF during peak fruiting was only slightly higher (~4%) than the LF management. In small plots, yields obtained with high-frequency irrigation for the entire season were significantly higher (16%) than the LF, while with high-frequency during rapid fruiting, they were 7% higher than LF. The increase in yield due to high-frequency irrigation in the small plots was about the same as that found in a previous study in 1993 (15 and 11%). The analysis of growth data has not been completed.

INTERPRETATION: Devices to smooth and compact furrows, such as the torpedo device used in this study, increase water conveyance across furrows in level basins. The advantage of more rapid and uniform advance times should significantly increase water application efficiencies during early season irrigation when light applications are desired. This work has also shown that light, frequent applications in basins during rapid fruiting are physically possible in sandy loam soils. However, the effect of this practice on lint yields in 1994 was quite small in the level basin study. Although high-frequency during rapid fruiting did produce somewhat larger increases in yield over low-frequency (7-11%) in the small plot studies of 1993 and 1994, the increase was still considerably lower than that found by other investigators. One reason may be that the cotton grown in the current studies was a short-season, determinant cultivar. Further studies of this approach to irrigation management are needed to establish specific practices that optimize cotton yields in level basins.

FUTURE PLANS: Development of high-frequency, small-volume, level basin irrigation will continue in 1995. Future work includes plans to implement another cotton irrigation study in large basins. This work will also evaluate season-long high-frequency irrigation in addition to the peak fruiting high-frequency management. Plans are also being developed to begin studies of this irrigation management approach on surface-irrigated vegetable crops.

COOPERATORS: D.D. Fangmeier, Agricultural and Biosystems Engineering Department, The University of Arizona.

Table 1. 1994 level basin irrigation schedules and application efficiencies.

Irrigation Number	Dates	Irrigation Management	Water Requirement (mm)	Basin Inflow Rate (lps)	Application Time (min)	Gross Depth of Application (mm)	Water Requirement / Gross Depth
Pre-plant	3/30-4/1	HF	~150	113	102	193	0.78
		LF	~150	118	98	193	0.78
1	5/10-5/11	HF	60	113	55	104	0.54
		LF	60	113	55	104	0.54
2	6/6-6/8	HF	82	86	63	91	0.90
		LF	82	86	88	125	0.66
3	6/20-6/24	HF	106	92	69	106	1.00
		LF	100	93	74	115	0.87
4	6/29-7/1	HF	67	83	60	83	0.81
5	7/5-7/8	HF	65	86	60	86	0.76
		LF	134	86	90	130	1.00
6	7/13-7/18	HF	86	100	55	96	0.90
		LF	112	93	87	138	0.81
7	7/19-7/21	HF	50	85	40	57	0.88
8	7/27-7/29	HF	61	85	43	62	0.98
		LF	94	85	66	93	1.00
9	8/9-8/11	HF	101	89	80	118	0.86
		LF	83	94	77	120	0.77
	TOTAL	HF	828	---	---	1000	----
		LF	815	---	---	1025	----

Table 2. Number of irrigations, total water applied, and lint yield for irrigation managements, level basins (a), small plots (b).

	Irrigation Management	Number of Irrigations	Total Water Applied (mm)	Lint Yield (kg/ha)	High-Frequency / Low-Frequency
(a)	Low-Frequency	8	1025	1360	-----
	High-Frequency (peak fruiting)	10	1000	1410	1.04
(b)	Low-Frequency	9	985	1120	-----
	High-Frequency (peak fruiting)	11	985	1200	1.07
	High-Frequency (all season)	14	980	1300	1.16

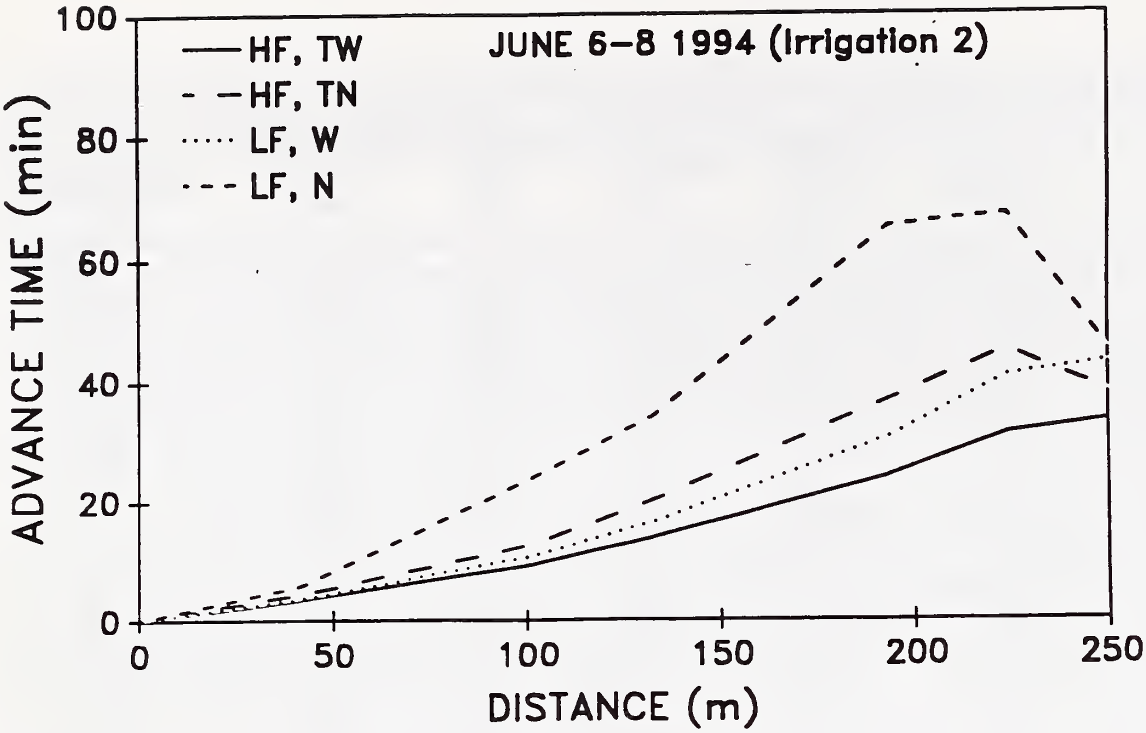

Figure 1. Average furrow advance times for early June irrigation in High-Frequency (HF) and Low-Frequency (LF) managements in 1994. T indicates that the furrows were smoothed and compacted, W and N indicate wheel and nonwheel rows.

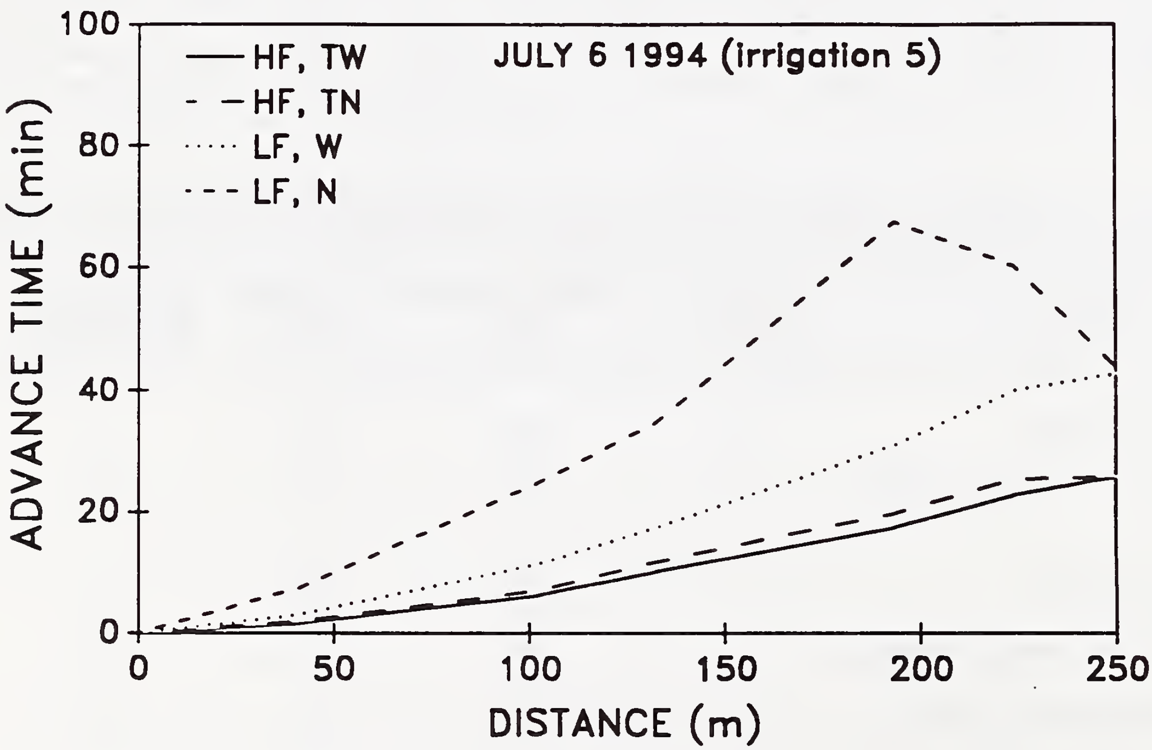

Figure 2. Average furrow advance times for early July irrigation in High-Frequency (HF) and Low-Frequency (LF) managements in 1994. T indicates that the furrows were smoothed and compacted; W and N indicate wheel and nonwheel rows

SURFACE IRRIGATION MODELING

T.S. Strelkoff, Research Hydraulic Engineer;
and A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Throughout the irrigated world, water is applied to fields unevenly and locally in excessive amounts, leading to wastage and to pollution of surface and groundwaters receiving the excess. The interaction of the many variables significantly influencing the movement of irrigation streams down fields, and, ultimately, the distribution of infiltrated water and the amount of runoff from the irrigation, is too complicated for simple calculation. A mathematical model--a numerical computer solution of the pertinent governing equations--supplied with the conditions of the irrigation can, on the other hand, allow rapid determination of the consequences of a given physical design and management procedure. Systematic, repeated simulation allows determination of design parameters to yield optimum uniformity of infiltrated water and minimum runoff from the end of the field, as reported under the title, "Surface Irrigation System Evaluation, Design, and Management." This, in turn, can reduce the degradation of groundwater supplies by excess irrigation water, contaminated by fertilizers and pesticides, percolating below the root zone of the crop. Similarly, reduction and re-use of field runoff protects surfacewater supplies downstream from irrigated fields.

Current models of surface irrigation require further development to extend the range of conditions they are designed to simulate and to increase the reliability of their mathematical procedures. New irrigation techniques generally precede attempts at simulation, so models must be revised to allow theoretical study of the innovations. Furthermore, present models do not always complete a simulation. A physical condition that can arise with cut-back flows is a temporary retreat of the leading front of the stream, eventually halted and once again moving forward. The present model simulates this motion only crudely.

In addition, certain flow conditions, notably, very slow advance, on the order of a foot per minute, with potential, incipient front-end recession, present poorly posed problems, both physically and mathematically. A potential computer response is the generation of a negative depth with consequent premature front-end recession. Because very slow advance is a common feature in sophisticated management of surface irrigation, a number of cooperators have pointed out the need for successful, routine simulation of this regime.

The present treatment of surges overtaking previous releases is not realistic and needs improvement. Likewise, overflow into a drainage ditch through critical depth, as currently postulated, is not a realistic representation of current farm management--typically, the drainage ditch is given a sufficient depth of water to prevent the erosion that would occur if critical conditions were in fact present at furrow end.

The current ARS surface irrigation model, furthermore, requires data entry more complicated than many potential users are willing to negotiate.

APPROACH: User-friendly, menu-driven data input and output, the latter as graphs and text, are to be linked to a reliable simulation engine based on mathematical expression of physical laws governing water flow. Constants in commonly accepted empirical equations for infiltration and roughness are to be entered as input. Program development involves extensive coding in both FORTRAN and C++.

FINDINGS: An experimental version of a user-friendly, menu-driven surface-irrigation model is approaching completion and distribution to cooperating researchers. It has proved possible to link a user-friendly graphics-oriented interface, comprised of ZINC menus programmed in WATCOM C++ code, to a simulation engine, written and compiled in WATCOM FORTRAN. The result is a single 1.2MB executable file. On contemporary PCs possessing extended memory beyond the 640K DOS range, execution is enabled through the DOS4GW memory manager distributed by WATCOM. The new configuration has the potential for greater reliability than the previously used combination of stand-alone modules manipulated by a batch file capable of reading DOS exit codes. Furthermore, array sizes are no longer limited by the 640K ceiling, allowing simulation of complex physical circumstances. A new graphical output screen (see Fig. 1, for example) has been added to allow the most important output variables--infiltration distribution, runoff, efficiency, and deficits--to be viewed as both graphics and text on a single screen for user convenience.

Simulated stream-controlled cutback and cutoff have been extended to the case of sloping-border irrigation for which the design condition is cutoff such that the infiltration requirement is just met at the upstream end when recession begins. In contrast to the model's earlier ability to control inflow by *monitoring* simulated stream

study of lag time in sloping borders was restated in terms of new dimensionless variables allowing development of a simple, explicit fitted algebraic expression for predicted lag time.[1]

A concentrated program for increasing simulation reliability under difficult circumstances is underway, particularly for sharply varying bottom configuration. The simulation shown in figure 2 for flow over a poorly leveled field fails if the inflow rate is much reduced. In general, the nonlinear solution equations become extremely sensitive to the initial guesses for the variables. For example, a first guess at a bottom-elevation peak for flow depth that is much larger than the down-slope normal depth corresponding to the first-guess discharge at the peak leads to negative depths or negative advance in the next iteration. It is hydraulically impossible to transition gradually from a depth higher than normal to normal depth in a channel of mild slope. On the other hand, it was found that the transition from a fast moving stream on a steep downslope to a nearly level pool occasioned by a sharp rise in bottom elevation must have enough grid points to define it smoothly and prevent occurrence of negative depth in the iterations. It now appears that some testing will have to be performed by the model at major changes in slope to provide appropriate grid spacing and initial guesses for the variables. Under less stringent conditions, arbitrary initial guesses based on stream variables at the end of the last time step prove adequate to allow iterative approach to the correct values at the new time level.

INTERPRETATION: To make a significant impact on surface-irrigation design and practice, computer models of the process must be of broad scope, fast, and reliable, yielding simulations for every reasonable combination of circumstances, and with convenient, user-friendly data input and graphical display of the results of any given set of design and management parameters. This is the aim of current development. A simulation model capable of providing quick results for various test combinations of design and management parameters would allow these to be optimized.

FUTURE PLANS: Current deficiencies in model behavior as outlined above will be addressed, exploiting the ZINC-WATCOM development-software combination.

COOPERATORS: D.D. Fangmeier, University of Arizona; Dr. Behzad Izadi, University of Idaho; Keith Admire, Natural Resources Conservation Service (formerly, SCS), Dexter, MO; Dr. Marshall English, Oregon State University.

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[1]Strelkoff, T.S. 1994. Incorporating Management Design into Surface Irrigation Simulation. Paper No. 94-2139, presented at the International Summer Meeting of the ASAE, Crown Center, Kansas City, Missouri, June 19-22; pp 1-21.

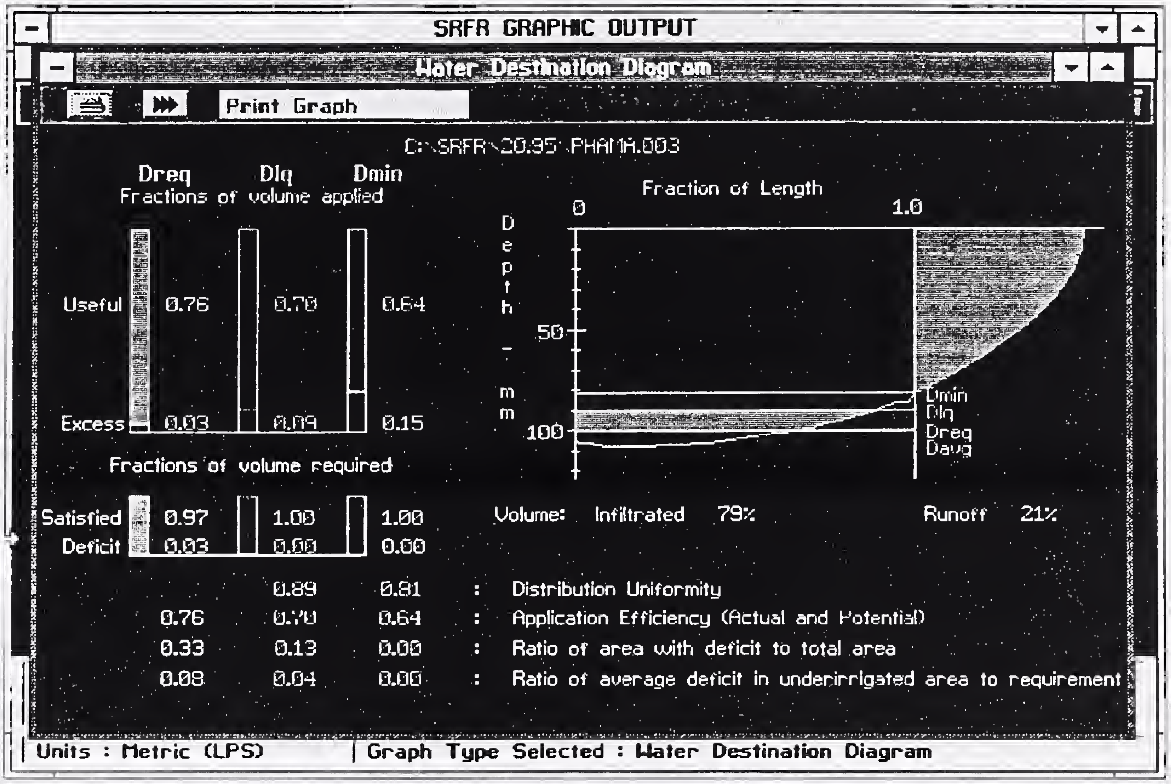

Figure 1. Water-destination diagram.

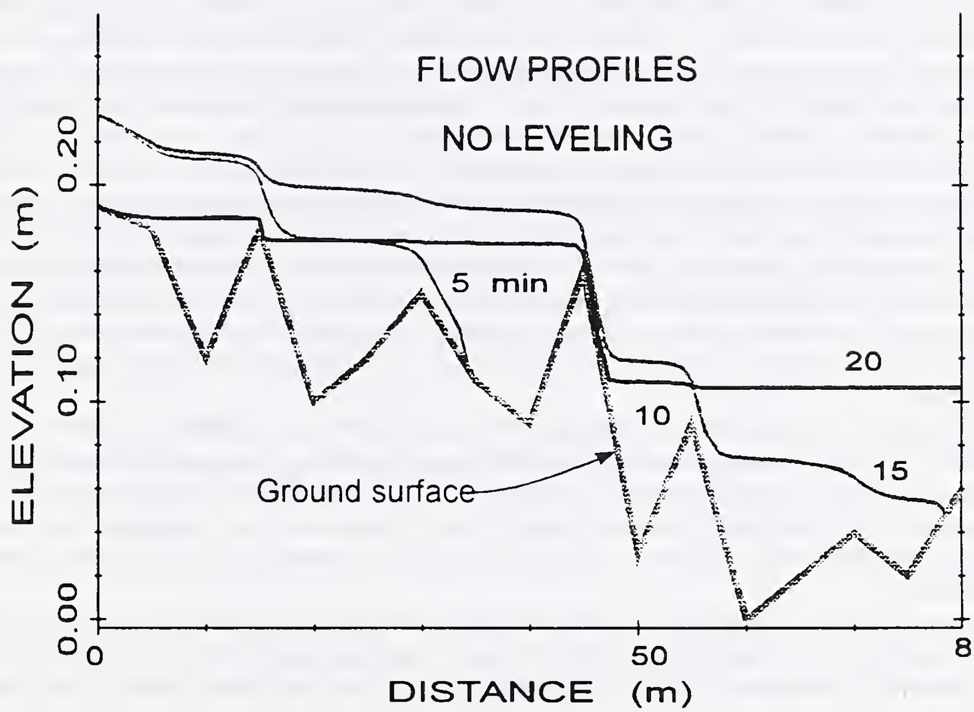

Figure 2. Simulated flow profiles.

SURFACE IRRIGATION SYSTEM EVALUATION, DESIGN, AND MANAGEMENT

A.J. Clemmens, Supervisory Research Hydraulic Engineer; T.S. Strelkoff, Research Hydraulic Engineer
A.R. Dedrick, Supervisory Agricultural Engineer; E. Bautista, Agricultural Engineer; and
R.J. Strand, Computer Programmer

PROBLEM: Mathematical models of water flow in surface irrigation have been developed over the last two decades. These are predictive models; that is, the user supplies the actual conditions, and the model determines the results of the irrigation. Design represents the opposite situation; for a desired irrigation result or output, the designer wants to know how to specify inputs: field dimensions and operating procedures. This is complicated by infiltration and roughness conditions, which are generally not known, and, furthermore, change over the season. Most existing design procedures specify recommended field dimensions but rarely recommend operating procedures. Thus, even a good design may result in poor performance unless the operator is given appropriate operational guidelines. In many cases, design is based on procedures or equations that have only a limited range of usefulness. It is generally difficult for the designer to know how a surface irrigation system will perform until it is laid out and irrigations commence. Analysis based on computer simulation of unsteady flow has been the most reliable design tool, but currently is complicated to use.

One of the difficulties in applying computer simulation models is the lack of information by the designer on parameters that define field conditions, particularly infiltration and roughness. Existing irrigation evaluation techniques can be used to define some of these parameters. Further, while a number of evaluation techniques are available, different techniques are appropriate under different conditions. Little analysis has been done on the range of usefulness of the various methods and in defining how much data is really necessary for an effective determination of field parameters. For example, several research studies have shown that a constant Manning roughness value for vegetative borders, independent of flow depth, may not be appropriate. Other expressions have been proposed.

The objective of this project is to develop user-friendly software for the evaluation, design, and management of surface irrigation systems that is usable in a variety of surface irrigation settings.

APPROACH: Reliable predictive models are the first step in the development of surface irrigation software. Model development is discussed "Surface Irrigation Modeling" in this report. There are two approaches to developing design results from simulation: 1) to look up results already generated from a simulation model, or 2) to search for an acceptable (or optimal) design solution by iterating with the simulation model. With current computing machines, the former is still preferred; however, as increasingly faster machines become available, the latter provides more latitude in design objectives and field conditions.

Generalized design and management guidelines have yet to be developed from the models. These guidelines can be in the form of tabulated results, regression equations, or procedures for systematically applying the predictive models. This step is necessary for practical application of predictive models. Several approaches will be taken in the development of these design guidelines. They include the development of 1) nondimensional solutions for general problems (e.g., optimal designs) that can be computer-coded, 2) search procedures for more specific problems (i.e., a series of simulations with inputs that are varied to achieve the desired outcome), 3) design procedures that take into account the changes in field parameters that occur over the season, and 4) sensitivity analysis of design input.

Generalized design results for level basins previously were developed based on NRCS (formerly SCS) design procedures. However, Wattenburger and Clyma developed design solutions based on cutoff at the end of advance, which may be more applicable for level basin design where flow rates are unreliable. Field experience indicates that most irrigators use a spot in the field to determine when to cut off the stream (i.e., something less than the end of the field). This suggests that design (and thus, any design procedures or solutions proposed) should consider the operator's cutoff criteria.

In addition, one must be able to include other factors that affect uniformity and efficiency, namely, soil spatial variability, surface irregularities, and nonuniform inflow streams. Various studies will be conducted to assess the impact of these conditions. Procedures will then be developed to account for these factors in the design and operating procedures.

One limitation of existing programs is that the user must be able to quantify field conditions for infiltration and roughness. There is a need for a general program on field evaluation procedures to assist users in determining field conditions and parameters for input into these design and operation programs.

Efficient and robust search procedures need to be developed for finding optimal designs. Most search procedures are not totally reliable when applied to surface irrigation modeling.

FINDINGS: The nondimensional design results for level basins were previously coded into a menu-driven design program. This program, BASIN, was intended only to replace the NRCS design charts. New procedures were developed to include design based on advance distance at cutoff (see fig. 1). These new routines have been added to BASIN. It was found that evaluation of the results of a given design was needed to make the program more useful; thus, an Operation Evaluation option was added so that the user could determine how a basin might perform under different conditions after it was constructed. This option is equivalent to a simulation, although the program just does a search through existing simulation results.

Findings are also reported under two related projects: "Modeling the Influence of Land Leveling Precision on Surface Irrigation Performance" and "Software for Design of Sloping Border Irrigation Systems." Under the former project, analyses were performed to determine the influence of a nonlevel field surface on uniformity, when statistical methods could be used to represent this influence, and when the nonlevelness significantly influenced advance (making the statistical procedures no longer sufficient).

Initial performance curves for low-gradient sloping borders have been developed. An example is given in figure 2. Further analysis and development are needed to make these into useful solutions for design.

Initial work has begun on the development of software for the evaluation of surface irrigation events. Routines for curve fitting infiltration data have been written. Also, procedures for determining infiltration constants from subsurface volume over time, derived from field measurements have been written.

An overview of the literature on the use of dimensional analysis in surface irrigation was completed and is in press. This document provides the framework for future research and development in this area.

INTERPRETATION: While significant advancements have been made on the development of predictive models, significant impact will occur when these models can be incorporated into some form of user-friendly software. Only in this way will these models impact water use efficiency in irrigated agriculture. This must be done in the context of grower management practices.

FUTURE PLANS: The BASIN program, including a short users' manual, was completed and released during 1994. In 1995, work will start on adding the influence of land-leveling precision on distribution uniformity to BASIN, based on the results of analysis discussed above.

The project to develop design solutions for low-gradient, blocked end borders with The University of Arizona will continue. These are a logical extension of the solutions for level basins.

Further analysis of simple evaluation procedures will be conducted. Also, relationships for expressing vegetative resistance in cropped basins and borders will be examined.

Long-range plans are to develop a general software package for surface irrigation systems along the lines of BASIN but expanded to include sloping borders and furrows and to include the actual simulation model as well as generated design results and evaluations.

COOPERATORS: N.D. Katopodes, University of Michigan; D.D. Fangmeier, University of Arizona; T.A. McMahon, University of Melbourne; W. Clyma, Colorado State University.

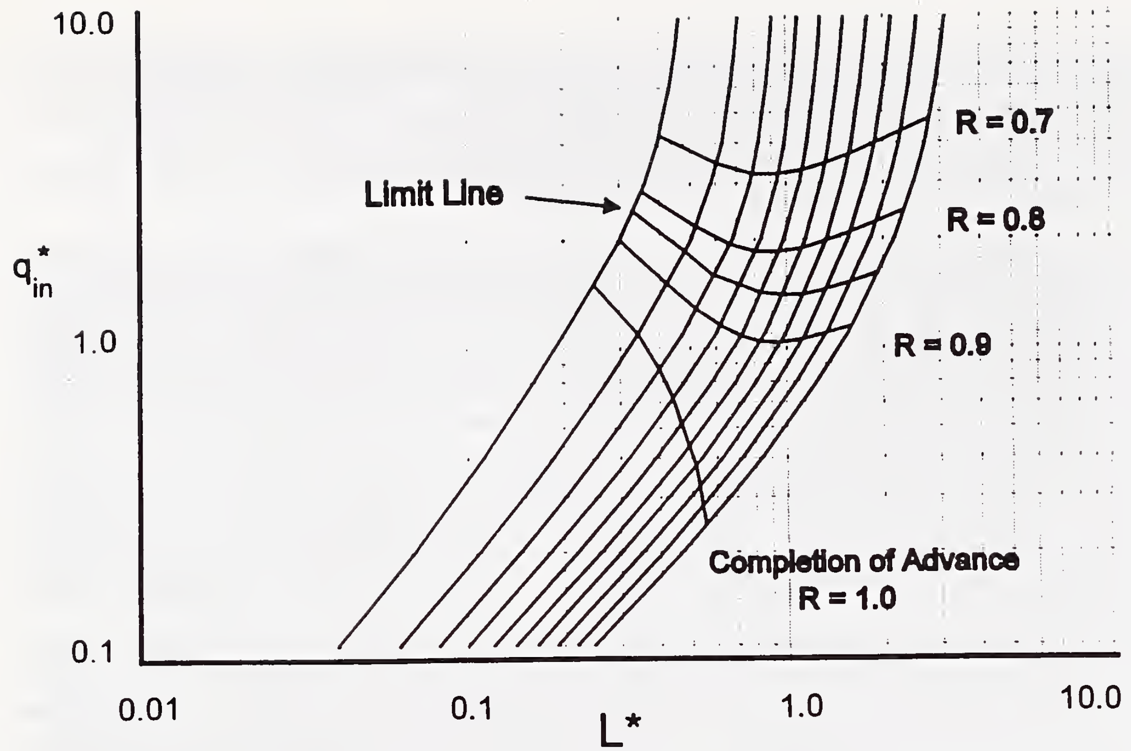

Figure 1. Level basin design charts showing the completion of advance design (a=0.5).

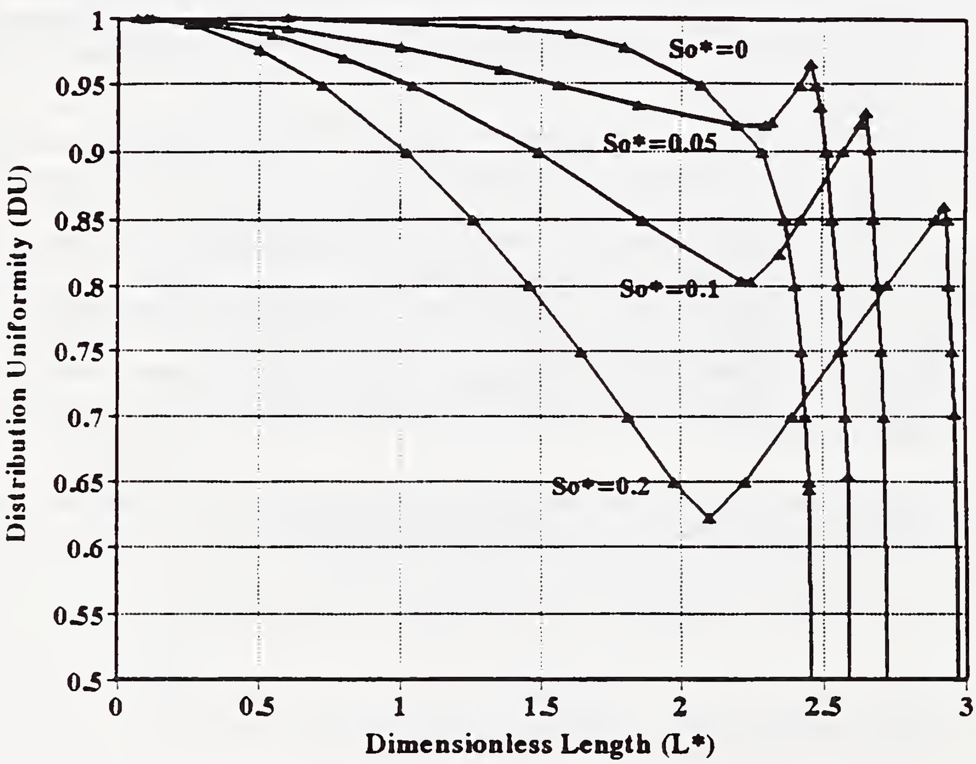

Figure 2. Low-gradient border irrigation performance curves showing influence of slope and length on Distribution Uniformity (for one particular set of field conditions).

SOFTWARE FOR DESIGN OF SLOPING BORDER IRRIGATION SYSTEMS

T.S. Strelkoff, Research Hydraulic Engineer;
and A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Rigorous, scientific bases for the design and management of highly efficient level basins are well established, and design software development is well underway (see "Surface Irrigation System Evaluation, Design, and Management," in this report). On the other hand, design and operation of graded fields with tailwater runoff are largely empirical and commonly depend a great deal on individual judgment and experience; formal design procedures such as those of the NRCS (formerly SCS) (1974) are based partially on broad assumptions of uncertain applicability. Efficiencies of water use in such fields can lag those in level basins by 20% or more. Yet in some areas, such fields represent the predominant layout. For example, in the Phoenix AMA (Active Management Area, Arizona Department of Water Resources) about 65% of the surface-irrigated land is in graded borders, and even a 10% increase in efficiency would save 115,000 acre-feet annually. Conversion to level basins is not always technically feasible, as when field slope is great and agricultural soils shallow. Furthermore, the cost of conversion to level basins or capital-intensive systems such as LEPA (low-energy precision applications) or micro-irrigation can be substantial. With irrigated farming in many areas under severe economic pressure, attainment of conservation goals without expensive conversions is especially attractive.

To use computer models in design directly, the engineer would perform a series of simulations, changing the design parameters from one to the next in the search for an optimum. But although contemporary computer equipment requires only a few minutes or less to predict the results of one or another design or management practice, engineers have been slow to incorporate simulation into their design procedures. In part, this is due to complicated data entry--for even simple problems--into elaborate models able, in principle, to simulate complicated field situations. Difficult simulations occasionally execute for many minutes. Simulations occasionally abort under some sets of input variables. These problems currently are being addressed at the USWCL by the development of user-friendly, menu-driven front ends, graphical output modules, and improved simulation techniques (see "Surface Irrigation Modeling," in this report). Still, at best, a simulation yields the results for only one set of design parameters and one set of management parameters. Given the simulated performance stemming from a particular, trial, set of design variables, it is difficult for designers to suggest appropriate changes in the trial values until they perceive the trends in performance with changes in those variables. One reason for the popularity of the NRCS design charts is that over several pages of graphs, the behavior of the resultant irrigation as the design variables are changed can be viewed, however incompletely or inaccurately, in the course of seeking an optimum combination.

APPROACH: In earlier studies (Strelkoff and Clemmens, 1981; Shatanawi and Strelkoff, 1984a, b) several thousand dimensionless simulations were performed. Nondimensional representation was employed to allow coverage, with only this number of simulations, of the whole spectrum of irrigations in sloping borders with tailwater runoff. It proved possible to fit the resultant distributions of infiltrated water by a two-parameter function with no more than 5% error. Dimensionless advance curves and curves evaluating the distribution shape parameters constitute the output from the earlier work.

Given a real or hypothetical design border, with length, width, slope, roughness, infiltration, inflow rate, and application time (or advance distance when inflow is cut off), all the conditions governing the irrigation are known, and it could be simulated. On the other hand, the appropriate *dimensionless* input variables can now be determined for entry into the stored dimensionless curves, and any performance indicator of interest (distribution uniformity, runoff, application efficiency, etc.) can be derived from the resultant shape parameters far more quickly.

More to the point, with just infiltration, slope, and roughness entered for a field and the target infiltration requirement for the irrigation, the variation of a chosen performance parameter with border length and inflow rate can be displayed on the screen. Thus designers can perceive the behavioral trends and make their selections accordingly.

In an alternate approach, all of the geometric and hydraulic characteristics of a border can be specified. The screen would then show the variation in performance with inflow rate and infiltration requirement. This would allow the designer to consider, say, the water-conservation ramifications of frequent light applications as opposed to heavier applications at greater intervals.

FINDINGS: Work has been initiated on software to aid in sloping-border design and management through contract with the Arizona Department of Water Resources (ADWR). Data input to the computer program follows logic similar to that for input to the BASIN program. An initial version of the input menus has been written (see samples in figs. 1 and 2). A surface-irrigation software user's group has been established to review the work under this contract, and its initial review of the input menus has been accomplished.

INTERPRETATION: There is potential for achieving water conservation by improved design and management of sloping-border irrigation systems. The use of software based on mathematical simulations of irrigations under trial conditions can assist greatly in optimizing water use. A fast, reliable, user-friendly computer program showing the response of the irrigation system to variations in trial conditions would be attractive to potential users. These users would most likely be those persons advising growers--mobile evaluation laboratory personnel, NRCS field personnel, extension personnel, consultants, and potentially, irrigation districts.

FUTURE PLANS: The existing dimensionless simulation data will be scanned, digitized and entered into program arrays. Appropriate computation and interpolation algorithms for access to and withdrawal from the data bank will be established and coded into the software. Algorithms for textual and graphical presentation of various choices of design information will be added. Documentation will be provided.

COOPERATORS: Alan Fehrman, ADWR, Phoenix; Harold Blume, Natural Resources Conservation Service (formerly, SCS), Phoenix; Chris Johnson, Buckeye-Roosevelt Natural Resources Conservation District; Ed Martin, University of Arizona Cooperative Extension.

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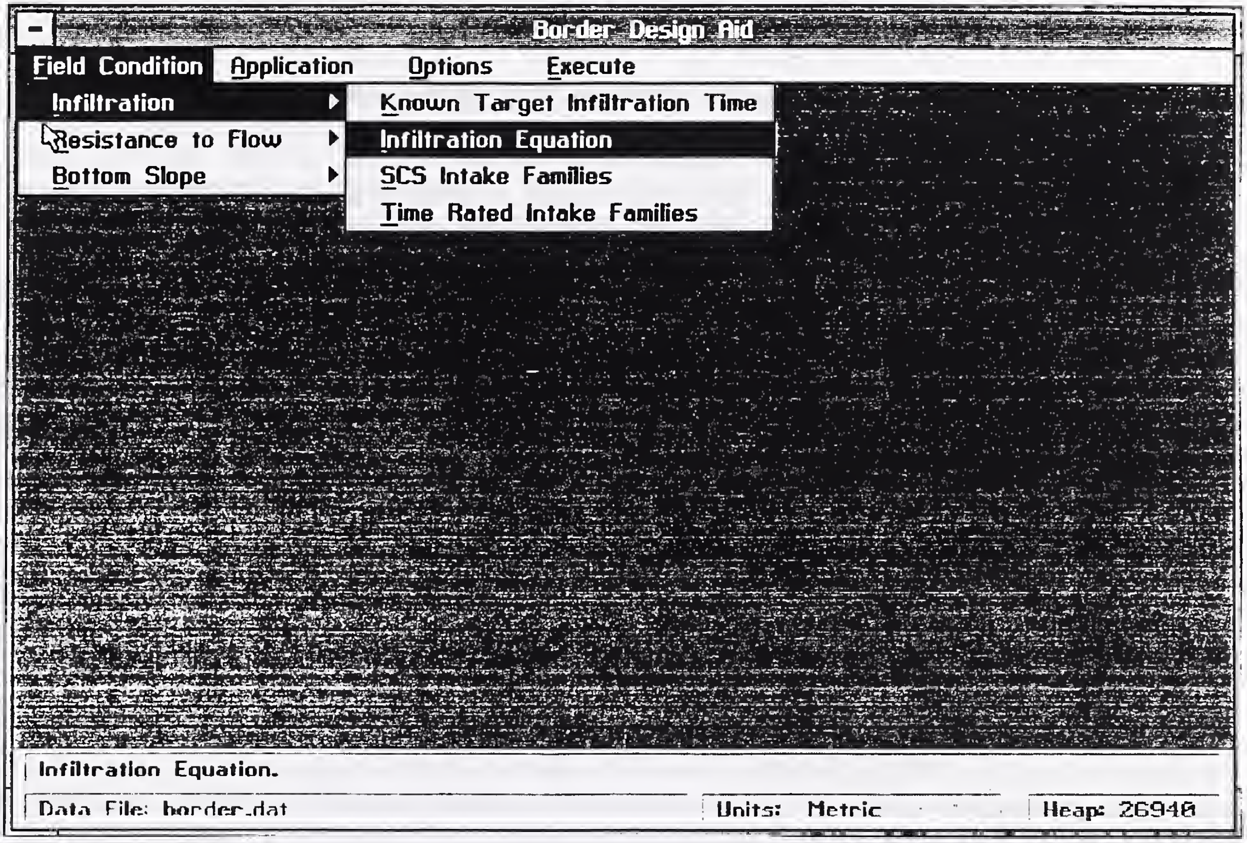

Figure 1. Sample menu.

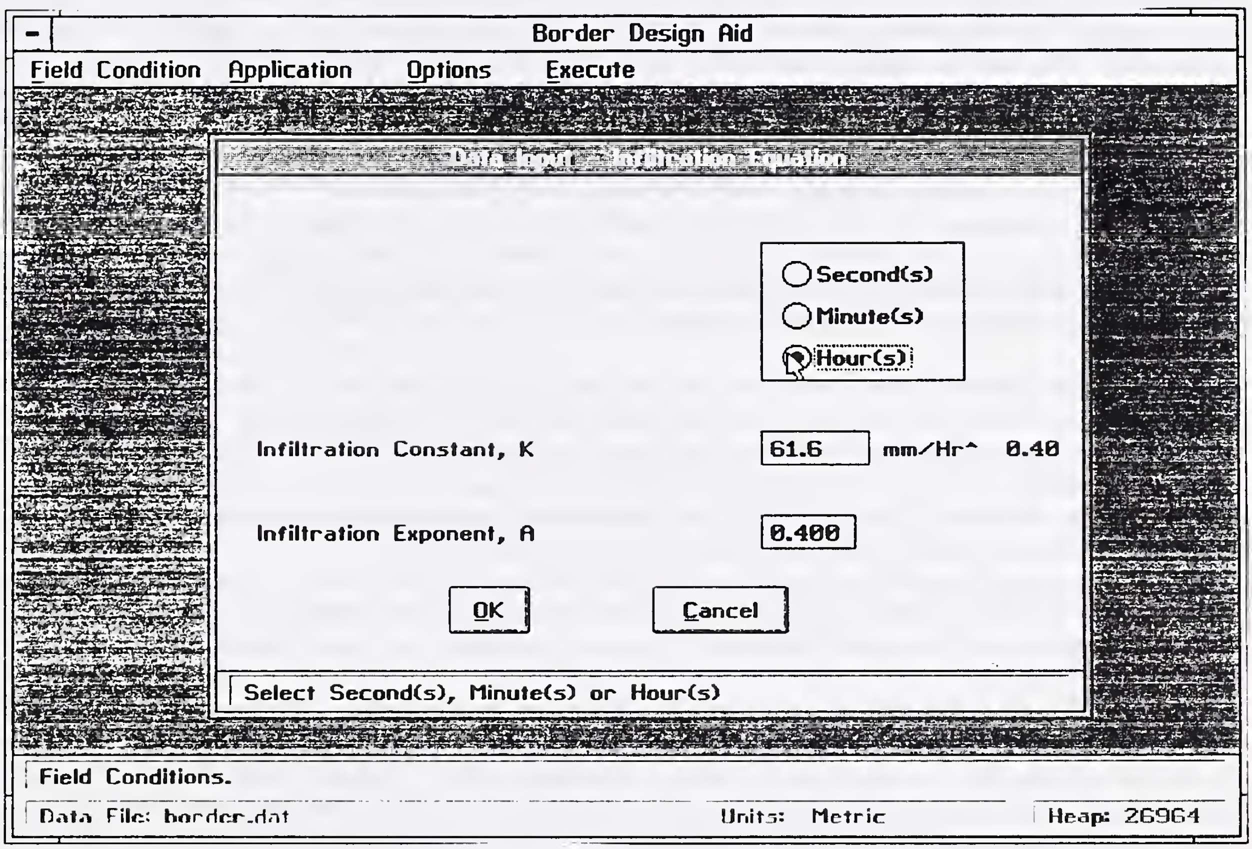

Figure 2. Sample data entry.

MODELING THE INFLUENCE OF LAND LEVELING PRECISION ON SURFACE IRRIGATION PERFORMANCE

A.J. Clemmens, Supervisory Research Hydraulic Engineer;
and T.S. Strelkoff, Research Hydraulic Engineer

PROBLEM: Surface irrigation systems inherently distribute water nonuniformly over the land area to be irrigated. Frequently, a contributing cause to this nonuniformity in basin irrigation is deviation of the field surface from a horizontal plane. Once the basin is filled and the water level is dropping, high areas in the field are dewatered first and receive relatively small amounts of infiltrated water. The lowest areas, with the greatest opportunity time for infiltration, receive the highest amounts. Furthermore, surface irregularities can reduce the speed of advance of the stream from the supply inlet in the process of filling the basin. With operating criteria based on advance over a theoretically level surface instead of one of nonuniform elevation, irrigation performance can prove less than expected.

Nonuniform distribution of water can cause a number of problems. Areas that receive too little water can exhibit crop stress and salinization of the soil. Too much water can leach fertilizers from the root zone and contribute to rising water tables, again potentially leading to salinization. When growers note crop stress in the high spots of a field, they tend to irrigate too often. This practice leads to excess deep percolation and rising water tables, which can affect adjacent lands as well. All of these factors can lead to reduced yield and can endanger the sustainability of crop production. The problems are much more acute on recently reclaimed lands because poor irrigation uniformities increase the amount of time needed to bring reclaimed land into full production.

Mathematical models of the advance and recession of water over a surface irrigated field are useful tools for predicting irrigation uniformity and efficiency. However, current models can handle only major undulations in the field surface, and only in one dimension. They cannot fully model the two-dimensional nature of water flow in basins or in multiple furrows.

APPROACH: National Agricultural Research Project (NARP), through the Office of Cooperative Interactions (OIC), has funded a cooperative project with the above title between this research unit and Moshtohor University in Egypt. Existing surface irrigation models are used in this study to take a first look at the effects of surface irregularities on uniformity. Part of this project is to extend the existing irrigation models to multiple furrows and/or two dimensions so that they can more adequately handle real field conditions. Field data are being collected to determine existing conditions in Egypt and to verify the models developed. Existing land leveling and tillage practices are being evaluated to determine their influence on leveling nonuniformity. Finally, assessments will be made regarding the magnitude of the impact of poor land leveling in Egypt, and design and management guidelines will be developed to aid in making decisions for improvement in surface irrigation practices, including recommendations on leveling and tillage practices. Ultimately, this is expected to improve the effectiveness of water use in irrigated agriculture, both in Egypt and the U.S.

FINDINGS: Initial field elevation survey data have been collected in Egypt to define the amount of nonuniformity in field surface elevations that exists under conventional-leveling and laser-leveling practices. Field evaluations of irrigation events were collected for both wheat (flat basin) and cotton (furrowed basin). Computer programs were developed to analyze the field data and determine infiltration and roughness parameters. These data were used to verify the SRFR simulation program. Analysis with this program can then be used to determine the influence of leveling precision on irrigation uniformity and efficiency, as shown in figure 1.

The cracking clay soils in the Nile delta do not act like cracking clay soils in the U.S. Infiltration rates remain high even after prolonged wetting, likely because of the high degree of flocculation in these soils. Subsequent simulations, based on the observed infiltration and roughness parameters, were used to verify the SRFR model for Egyptian conditions.

Several two-dimensional models of surface irrigation flow have been examined. The simpler methods will not accommodate an irregular bottom and are thus not useful for this study. A finite difference scheme based on a fixed grid of cells over the field was developed to model two-dimensional flow. With this model, depths are associated with the center of the cells, while discharges occur at the boundaries. Stability problems have been experienced, and a stability analysis currently is being conducted.

Furrow size and shape and tillage practices for cotton have been shown to have a significant effect on water advance and, thus, on irrigation uniformity on level basins in Egypt. Recommendations are for a minimum furrow spacing of 75 cm. Furrow smoothing will also speed advance. Equipment for minimum tillage should be considered for future work in this project.

Analysis has been performed to verify statistical methods for including the influence of land leveling precision on distribution uniformity. Monte Carlo simulations showed that the influence of uneven recession resulting from nonlevel soil surface could be accounted for with statistical equations. Unsteady flow simulations were used to determine the range of field nonlevelness that influences advance also significantly affects the resulting uniformity.

Training of Egyptian scientists has focused on irrigation hydraulics and modeling, flow measurement, field data collection procedures, and general mathematics and irrigation engineering.

INTERPRETATION: It is expected that leveling and tillage precision currently have a significant influence on both crop production and water management in Egypt. Frequently, farmers and government agencies do not have a full appreciation for the limitations on crop production and water management resulting from leveling and tillage imprecision, through their influence on irrigation uniformity. This study will provide information on the amount of influence of the leveling and tillage precision and recommendations for changes in current practices. This information could have a major influence on water management in Egypt.

FUTURE PLANS: The SRFR model will be used to analyze the influence of leveling precision on recession times and, thus, on irrigation uniformity. Statistical procedures will be added to the BASIN design program to take into account the influence of leveling precision on recession. The limits where the influence of leveling precision on advance (in one dimension) affects uniformity will be identified and added to BASIN.

Further work will be conducted to develop a two-dimensional basin model that can treat an irregular bottom. This model will be used to determine the influence of land-leveling precision on irrigation uniformity from both advance and recession. The results will be compared to the results of the one-dimensional model to determine whether the more comprehensive analysis with the 2-d model is necessary.

A multiple furrow model also will be developed so that the influences of leveling and tillage precision can be evaluated for a field (i.e., a series of furrows). This new model will be an extension of the SRFR model.

Additional field irrigation evaluations will be performed on wheat in Egypt under traditional and laser land leveling. These studies will provide additional information, which, in combination with the results of the analytical work, will be used to recommend the degree of land leveling precision necessary to achieve a desired level of irrigation performance and crop production.

Additional training will be provided during 1995 to Egyptian students in irrigation evaluations, instrumentation, and related topics.

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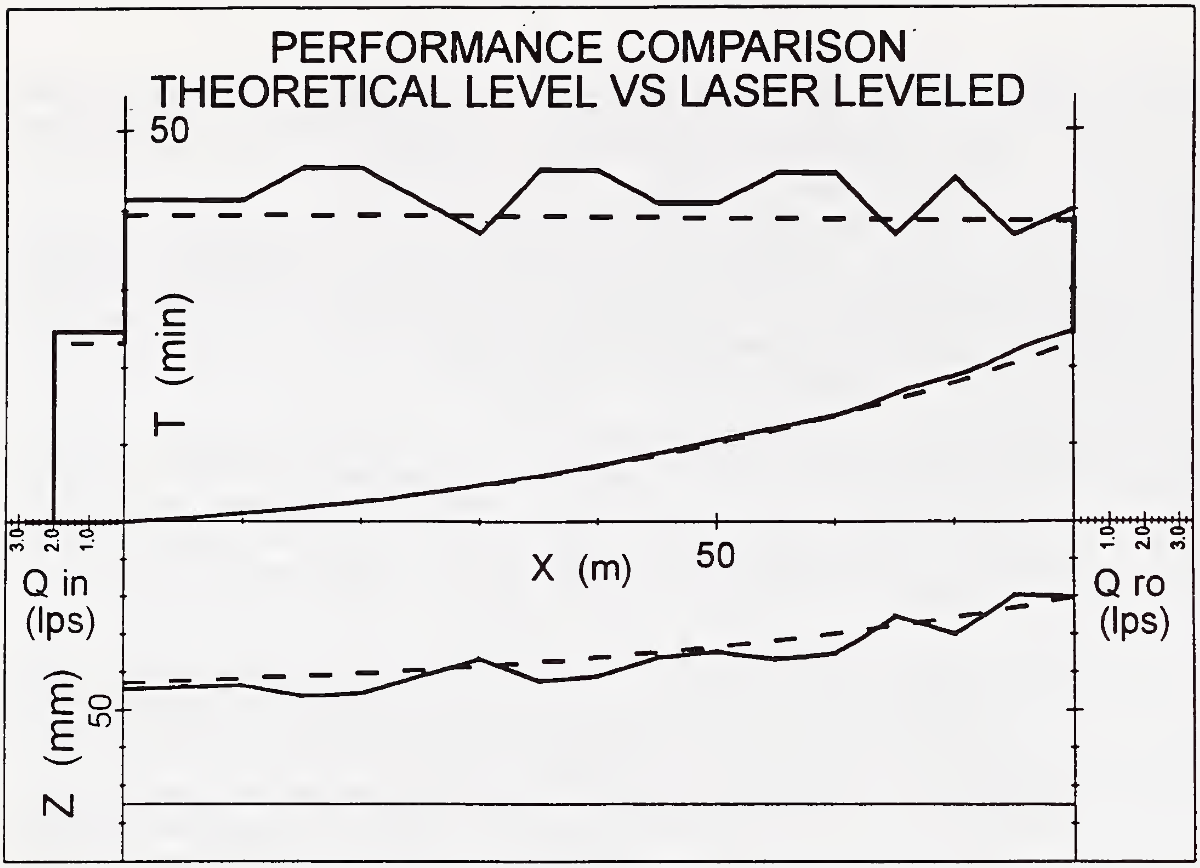

Figure 1. Inflow hydrographs, advance and recession curves, infiltration profiles for level (---) and laser-leveled (____) fields.

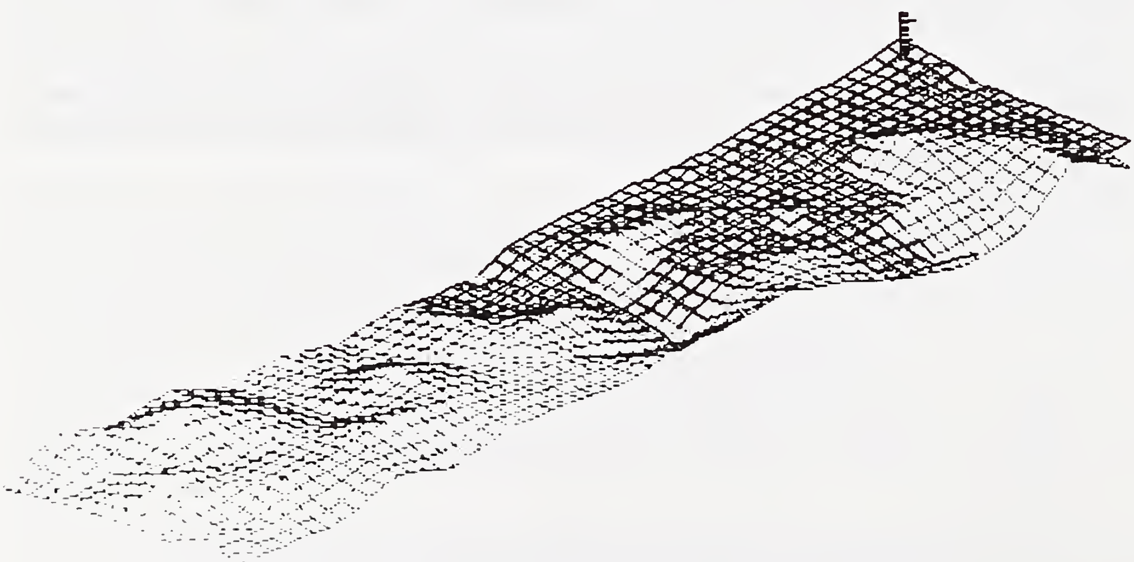

Figure 2. Advance of water over undulating field surface from prototype 2-D model.

CANAL BEHAVIOR AND RESPONSE TO TRANSIENTS

T.S. Strelkoff, Research Hydraulic Engineer;
and A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Efficient use of irrigation water often depends on the timely availability of the required flow rates for the required period of time. Research on these requirements is discussed in this report under "High-Frequency, Small-Volume Level Basin Irrigation for Cotton" and "Surface Irrigation System Evaluation, Design, and Management." The present report deals with the ability of a canal system to provide the required amounts to the users.

Even if the supply system consists of expensive pipelines, there is no guarantee that with a large number of users on a line, the pressure required to deliver a required rate at a distal point would be available. In the case of the far more economical and prevalent canal supply systems, delivery upon demand is considerably more problematical. In a closed conduit, even though pressure drops can limit the outflow at any offtake, at least one can say that the instantaneous sums of inflow and outflow discharges in a length of pipe are equal. An increase in flow rate at the upstream end of a closed conduit is reflected virtually instantaneously everywhere in the system. In an open channel, with the water surface free to rise or fall, changes in discharge propagate as large-scale gravity waves, moving not much faster than the water velocities themselves. It can be hours before a demand initiated at a downstream point can be satisfied by increases in discharge at the upstream end.

These circumstances have led, on the one extreme, to prior scheduling of user demands with canal operators, who make appropriate pump and control-gate settings in advance, and on the other, to a variety of supervisory or feed-back control schemes to respond to demands initiated at will by a user. Even with advance scheduling, the setting of the gates is often based on the subjective judgment and intuition of personnel with varying degrees of experience and is often inordinately time-consuming and inaccurate. Measures appropriate to anticipated demands are being studied with inverse schemes of solving the governing flow equations and are discussed in "Inverse Computational Methods for Open Channel Flow Control," in this report. The strategy of control based on measured canal responses to varying demands, in a feedback loop, is also reported in "Irrigation Canal Automation."

Given control measures have been found experientially to exhibit different degrees of success in different canals, depending upon slope, discharge, and other canal-flow parameters, so far in an unpredictable way. The present report deals with quantifying the influence of flow properties on canal response to control measures and other transients.

APPROACH: A program of numerical simulations of canal-pool response to standard control measures was initiated. An experimental generic model of unsteady flow was constructed instead of using existing industrial models because of the flexibility in internal and external conditions afforded by the custom model.

To cover the full range of canal parameters--base width, side slopes, bottom slope, roughness, length, gate openings, and initial discharge--without calling for an inordinate amount of experimentation and complexity in presenting results, the study is being conducted in dimensionless terms.

FINDINGS: The Saint-Venant equations of unsteady flow in an open channel have been recast in nondimensional form by referencing all discharges to an initial steady-state flow rate, all transverse dimensions (depth, width, elevation, etc.) to normal depth at the reference discharge, all longitudinal lengths to normal depth divided by bottom slope, and all times to a reference time equal to the time to traverse the reference length at normal velocity. The extraordinary simplification of this approach for steady-state flows can be seen in figure 1, showing all backwater profiles coalescing virtually into a single dimensionless curve, regardless of channel size, shape, slope, roughness, flow rate, and degree of checkup, as these are varied over ranges commonly encountered in irrigation canals: base width ranging from 0.5 to 3.0 times normal depth, side slopes ranging from 1.0 to 2.0, and normal Froude numbers ranging from 0.1 to 0.7. Steady-state profiles of *all* checked-up canal reaches are described by one or another portion of the generalized, nearly single, backwater curve shown.

The method of characteristics was selected as the solution mode for transient flows because of its theoretical correctness and its potential for disclosing facets of flow behavior that could be missed by more approximate schemes. Fortunately, it was available from previous work. Its drawback, inability to simulate flow after formation of a bore (without additional, potentially complicated, programming) was considered not too serious because this condition is not encountered very often (further calculation stops at the computed inception of a bore, and an alert

is printed). Programmed in nondimensional form, the solution technique serves as a subroutine to a calling program that automatically varies dimensionless input parameters over given ranges. Select measures of the canal-pool response are output to a file, one record per simulation. After an appropriate group of simulations has been run (perhaps several hundred), the data from the output file are analyzed and plotted by a separate stand-alone program.

Typical pool response to a sudden increase in discharge at a downstream offtake under conditions of "perfect control" without anticipation of flow changes, i.e., simultaneous, exact replacement of the offtake discharge at the upstream end, is displayed in figure 2. In this scenario, the gate opening, once set to afford a certain degree of checkup, remains fixed throughout the test; downstream from the gate, normal depth at the gate outflow is assumed to prevail, as if the test pool were followed by another, long canal pool of the same section. To avoid the issue of offtake-gate hydraulics, relating offtake flow to canal flow depth, the offtake discharge is assumed fixed, as if pumped.

INTERPRETATION: The exceptional benefits of nondimensional analyses of steady flow are not so apparent in unsteady flow, but still, substantial simplification of the problem is effected.

Immediately evident from the results is that even under conditions of perfect control, replacing offtake demands from upstream takes time, and that until the replenishments arrive in sufficient quantity, the depth at the offtake continues to fall. The longer the canal, the greater the offtake, and the greater the Froude number of the initial uniform flow, the greater is the drawdown. Curves such as in figure 2 quantify the behavior and show the conditions under which *anticipatory* regulation is mandatory in preventing excessive drawdown.

FUTURE PLANS: On the one hand, additional control scenarios will be investigated, in particular, specifying an inline outflow hydrograph. On the other hand, the generic canal model used in the analyses will be extended to include additional control-structure elements and upstream and downstream boundary conditions, and multiple pools, as well as an implicit, fixed-grid numerical solution scheme common in industrial models, for comparison with the method of characteristics. Capability of simulating additional regimes of flow behavior, such as supercritical flow and bore propagation, will also be investigated.

COOPERATORS: Jean-Luc Deltour, GERSAR-SCP, Societe du Canal du Provence, Aix-en Provence, France; Charles Burt, Calif. Polytechnic State University, San Luis Obispo, Calif.

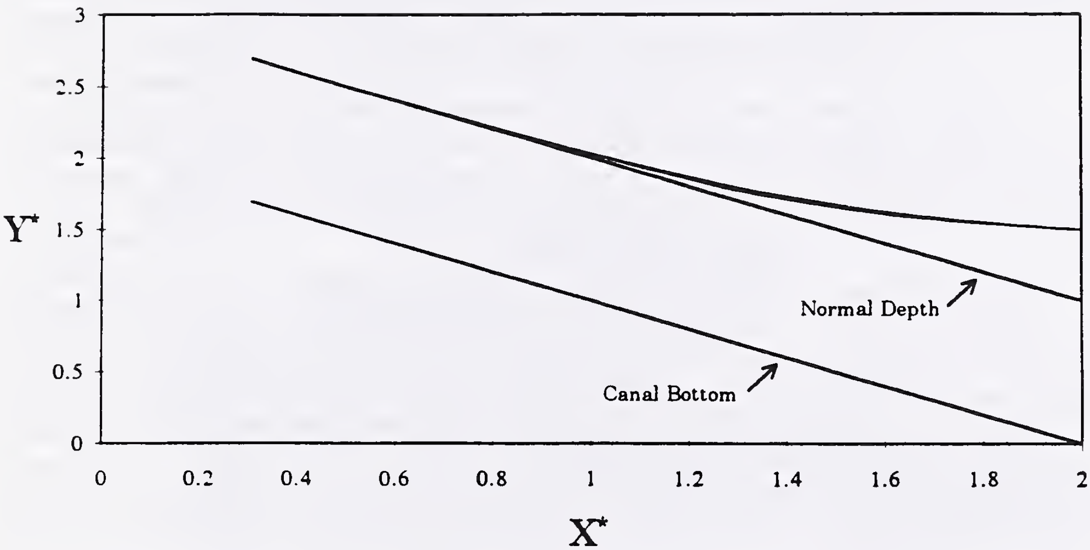

Figure 1. Dimensionless steady state backwater curves.

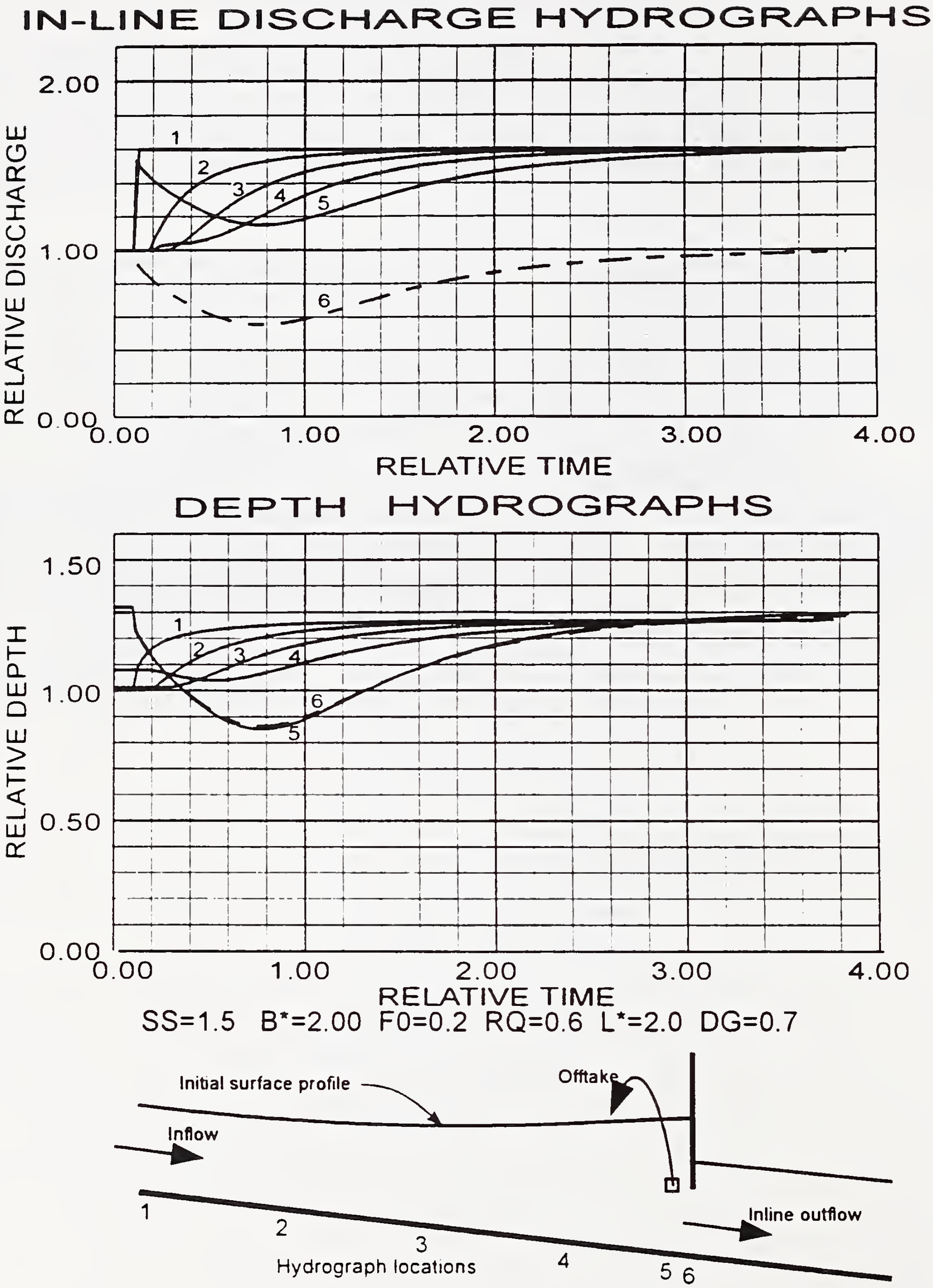

Figure 2. Perfect control--no anticipation of demand.

INVERSE COMPUTATIONAL METHODS FOR OPEN-CHANNEL FLOW CONTROL

E. Bautista, Agricultural Engineer; A. J. Clemmens, Supervisory Hydraulic Engineer;
and T.S. Strelkoff, Research Hydraulic Engineer

PROBLEM: An elementary problem in the regulation of open-channel water delivery systems is how to determine the operation of the system's control structures to obtain a prescribed variation in discharge and depth of flow at specified points of the system. Such an approach presupposes that water demands as a function of time are known. A computational procedure for solving this problem was first proposed by Wylie (1969). The method, known as "gate-stroking," solves the partial differential equation system of unsteady, gradually-varied open channel flow using the method of characteristics. The analysis begins with the specified time variations in discharge and depth at the downstream end of the system and proceeds backward in space and time until reaching the system's upstream boundary and initial state. The output is the gate motions needed to produce the controlled transient. This application of computational hydraulics is different from unsteady flow simulation problems in which solutions are generated forward in time, with values of depth and discharge along the canal known at the initial time, and for which the output is the resulting hydrograph at the distal end.

Although the gate-stroking method has been well established for some time, and an industrial-scale model has been developed and used by the U.S. Bureau of Reclamation (Falvey and Luning, 1979), European researchers (Chevereau, 1991; Liu et. al., 1992) recently proposed two distinct computational alternatives to solving the problem. The former author developed a finite difference solution based on Preissman's four-point implicit scheme (Liggett and Cunge, 1975). To generate a stable solution, more weight is given to the dependent variables at the current space line than at the previously calculated space line, downstream from the current line (fig. 1). This is different from the conventional application of the Preissman scheme to simulation problems in which values of the dependent variables at the current time line are given more weight than values at the previous time. Liu et. al. also used the Preissman scheme to formulate the finite difference equations but generated an explicit solution, starting at the top-right most computational cell, and moving cell-by-cell, first backward in space, and then backward in time. The procedure is initialized by assuming the new steady-state conditions at a nominal final time, thereby providing the values of the unknown discharge and depth of flow at the top-left corner of the first computational cell. Since discharge and depth are prescribed on the cell's right boundary, the problem reduces to solving a system of two equations and two unknowns (the dependent variables on the bottom-left computational node).

APPROACH: A study is being conducted to examine the computational properties of the gate-stroking, implicit, and explicit finite difference solution methods. Tests are being conducted with a wide range of canal properties. Results produced by the three models are being compared against each other and against results produced by forward simulation, i.e., by using a simulation model to compute the downstream hydrograph using the inverse solution as the upstream boundary condition. Method-of-characteristics and implicit finite-difference simulation models are being used for this purpose. This study is one element of a broader study which aims to examine the control characteristic of irrigation canals.

FINDINGS: Initial tests revealed important differences among computational procedures. Although reasonable results can be obtained with the explicit method of Liu et. al. (1992), the computed upstream hydrographs more often display erratic oscillations, a problem that is magnified with decreasing values of canal slope or of the time increment used in the calculations. This problem was attributed to the solution strategy, which as proposed, ignores information provided by the backward characteristic curve emanating from the downstream boundary of the system. In an attempt to address this problem, the code was rewritten to solve cell-by-cell, first in the negative time direction until reaching time zero, then advancing the solution to the next upstream space line, and continuing this process until reaching the upstream end of the canal. Computations appear to be unstable and, thus, unsatisfactory. Difficulties were also been experienced with Chevereau's implicit finite-difference solution, but of a different nature. The model as written uses local linearization to speed up the computations, resulting in significant loss of accuracy as the spatial step size increases and with increasing values of slope. This problem was overcome by implementing a fully nonlinear iterative solution (fig. 2). The upstream hydrographs computed with this improved implicit finite-difference procedure resemble those obtained with the gate-stroking method, although peaks and valleys are less pronounced, a result explained by the diffusive nature of the implicit method.

Examples were identified for which solutions were obtained with the implicit method but not with the gate-stroking model. A likely explanation for these results is that for these examples, the prescribed downstream flow schedule causes a hydraulic bore to form. Gate-stroking does not incorporate a specific routine to track this type of discontinuity in the flow profile, while Chevereau's implicit finite-difference solution, which is based on the conservative form of the governing equations, averages such discontinuities. Evidence to support this explanation is provided by the fact that when solutions generated with Chevereau's model to the above mentioned examples were used as an input to the characteristic forward simulation model, a hydraulic bore developed.

INTERPRETATION: Overall, operational schedules computed with the implicit finite difference solution scheme are comparable to those obtained with the method-of-characteristics approach. It is important to note that there are practical constraints to the application of the backward canal operation calculations, first because water demand schedules are usually not known ahead of time, and second because the computed gate or pump operations may be impractical or difficult to implement. Nevertheless, these techniques can be used to develop a control system when demands can be anticipated and, further, they are an aid to understanding the response of an irrigation delivery system to open-loop controls.

FUTURE PLANS: Systematic testing will be performed for a practical range of the design variables. Tests will also be conducted using nondimensional variables, and efforts will be made to find generalized relationships between canal properties and response characteristics (controllability).

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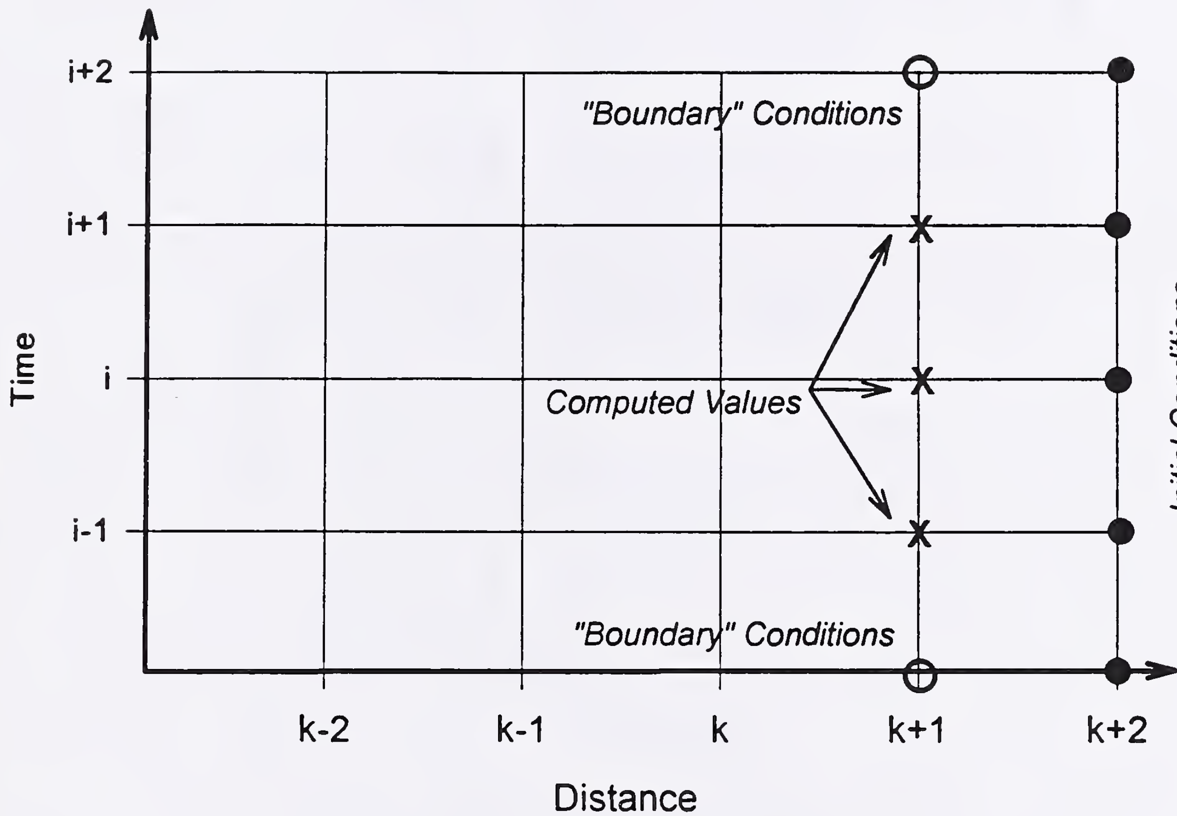

Figure 1. Inverse transient-control computation with implicit finite differences (Chevereau Method)

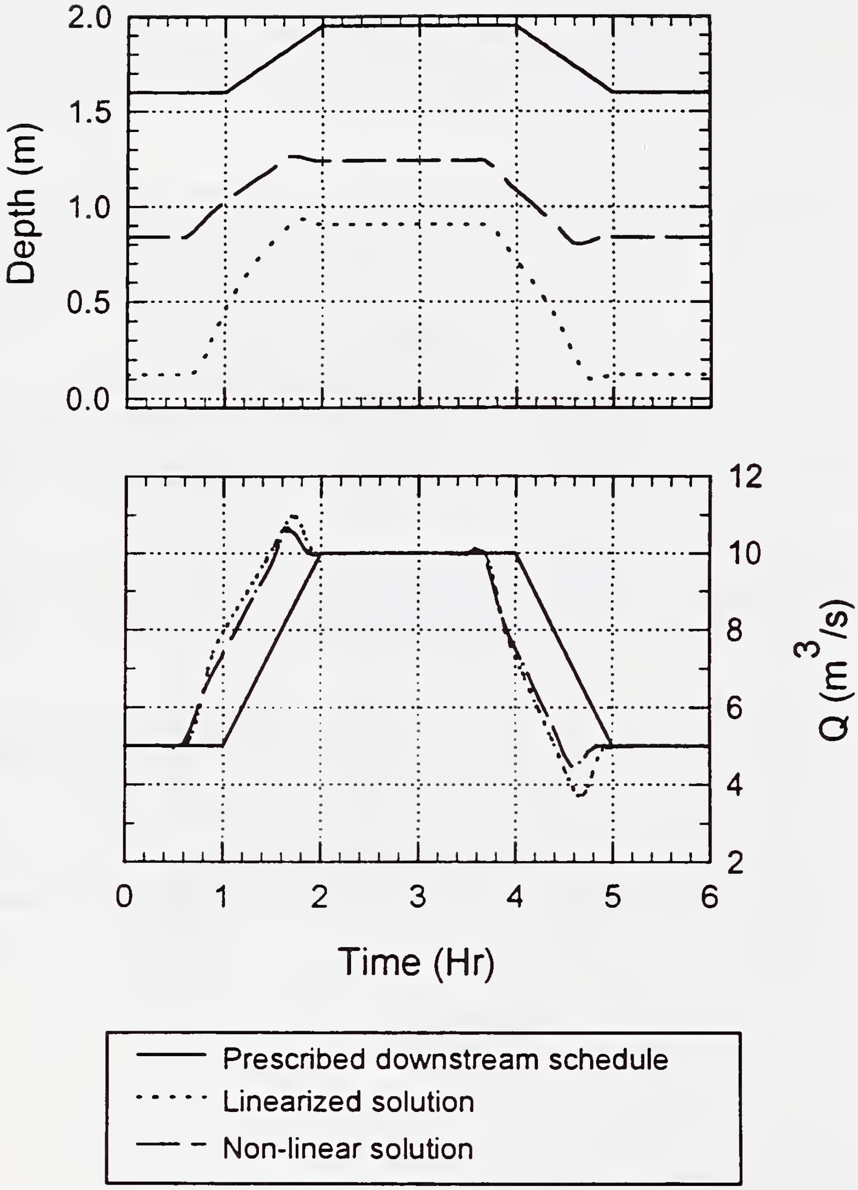

Figure 2. Comparison of upstream discharge and depth schedules computed with linear and non-linear implicit finite difference solution.

TECHNOLOGY FOR IMPROVED MANAGEMENT OF IRRIGATED AGRICULTURE

IRRIGATION FLOW MEASUREMENT STUDIES

J.A. Replogle, Research Hydraulic Engineer; B.T. Wahlin, Civil Engineer;
and A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Water flow measurement continues to be a major tool for improving irrigation water management to conserve water and energy in irrigated agriculture. Problems with flow rate devices include their relative complexity, required training level of field users, and economics of installation and operation. Other problems include (1) pipeline flows that take their water from canals, and which thus may carry trash unsuitable for propellers, or many other meters; (2) sensing a water surface reliably, economically, and accurately, while remaining compatible with data acquisition and control systems; and (3) point-velocity sensing for automatic laboratory data acquisition. Only some of these problems were addressed during this reporting period.

APPROACH: Several historical measuring techniques are being reevaluated because modern electronics and computer power have removed some of the limitations preventing wide application to irrigation flow metering. A general approach to evaluating all measuring devices involves carefully constructing or preparing devices for general hydraulic behavior testing as predicted by hydraulic theory. Devices currently active or previously mentioned as being under study are:

(a) *Float Velocity:* Multiple floats simultaneously dumped into and across concrete lined, trapezoidal channels (time for the lead particle to float from position A to position B provides information on channel roughness and velocity).
(b) *Trash Resistant Meters:* Propeller meters for trash-filled flows.
(c) *Rising-Bubble Technique:* A curtain of rising bubbles used to measure flow in earthen channels.
(d) *End-Cap Orifices:* Verification of end-cap orifice calibration.
(e) *Modifying Parshall Flumes:* Conversion of Parshall flumes to computable long-throated flumes.
(f) *DACL Valve Design:* New design for a dual-acting, controlled-leak (DACL) valve.
(g) *Books and Book Chapters:* Preparation of various book chapters and book revisions related to flow measurement and irrigation.

FINDINGS:

(a) *Float Velocity:* Several field tests using canal floats were completed in early spring. Difficulties with finding constant flows in the field compromised some of the results. Using special water depth sensing methods, we obtained good quality data on channel friction values. A complete analysis has not been made.
(b) *Trash Resistant Meters:* Laboratory checks of concept have been completed. Negotiations with a meter builder to construct industrial prototypes are underway.
(c) *Rising-Bubble Technique:* A heavy chain needed to complete the in-ditch part of the field equipment has been purchased. The method requires that the area of the bubbles' emergence from the channel bottom as viewed in plan be determined. This equipment is partly designed in several options but has not been not fabricated. The bubble-forming part of the equipment is used in the laboratory to verify velocity profiles in the Laboratory channel, figure 1.
(d) *End-Cap Orifices:* The calibration of end-cap orifices was confirmed using the laboratory weigh-tank system. Differences in calibrations were detected depending on whether the pressure tap was located on the flange of the orifice or whether it was three pipe diameters upstream from the orifice.
(e) *Modifying Parshall Flumes:* A one-foot fiberglass Parshall flume was installed for study in the laboratory. The unmodified Parshall flume was calibrated under unsubmerged conditions using the laboratory weigh-tank system. The initial calibration of the Parshall flume was approximately 4% lower than the historical discharge equation. After flow straighteners were added upstream from the approach section of the flume, the calibration difference reduced to -2%.
(f) *DACL Valve Design:* A prototype for the new DACL valve has been constructed. Concept passed preliminary and qualitatively tested.
(g) *Books and Book Chapters:* The book chapters are:
   - Sub-chapter (part of chapter 2) "Measurement of streamflow." *Handbook of Hydrology*. American Society of Civil Engineers. Replogle, ARS; and Riggs, USGS (final review).

- *Handbook of Water Resources*, Part III, Water Resources Supply, III.22 Irrigation Systems. Replogle, Clemmens, Jensen. Editor: Larry Mays (adjusting to reviewer comments).
- *Water Measurement Manual: A Water Resources Technical Publication*, U.S. Bureau of Reclamation. In cooperation with the Manual Revision Team (in preparation).
- *Design and Operation of Farm Irrigation Systems*, Editors: M. Jensen and R. Elliot. Revision and consolidation of chapters 8 and 11. Replogle, ARS; and Kruse, ARS (starting).

INTERPRETATIONS:

(a) *Float Velocity:* Tentative findings indicate that the maximum velocity filament can be measured reliably and that the relationship to average velocity is a predictable function of roughness height. Reliable methods to measure or characterize roughness have not been determined.

(b) *Trash Resistant Meters:* Prototypes are expected in the spring of 1995.

(c) *Rising-Bubble Technique:* Field equipment is within the state of the art and is expected to be field usable when assembly is completed.

(d) *End-Cap Orifices:* Flange taps (at or near the end of an-cap orifice) appear to be in a region of steep pressure gradients. This can give varying results for slight variations in tap location, particularly for large orifice ratios. Locating the tap near the orifice plane has the advantage of being in a region of flow stagnation, and the effects of poor pressure tap construction are less. Conversely, pressure taps located three pipe diameters upstream are in a high-speed flow region and require careful pressure tap construction regarding burrs, tap size, and tap straightness. The tests clarified the meaning of historical reports that appeared to describe varying results.

(e) *Modifying Parshall Flumes:* The -2% difference in calibration from standard equations could be due to the nonstandard entrance condition that was used in the laboratory set-up of the Parshall flume, but the difference is greatest at low flows when the entrance condition should be expected to have small influence.

(f) *DACL Valve Design:* Performance evaluation testing and durability testing are still needed.

(g) *Books and Book Chapters:* These books can positively influence irrigation flow metering and contribute to water resources functions well into the next century.

FUTURE PLANS:

(a) *Float Velocity:* Another useful piece of information that may be obtained from this study may come from looking at the amount of dispersion between the first and last float. From this dispersion, it is hoped that an indication of the channel roughness can be obtained.

(b) *Trash Resistant Meters:* Plans are to follow up on the prototype construction.

(c) *Rising-Bubble Technique:* Field test the equipment for convenience and accuracy in channels that are currently equipped with flumes so that comparisons can be made.

(d) *End-Cap Orifices:* An alternative pressure tapping system using a small tube with holes drilled through its wall to detect the pressure in the large pipe will be studied. The tube will be inserted through a sealed hole through the orifice plate and near the pipe wall. The drilled sensing holes will be about three pipe diameters upstream of the orifice plate when in place and will be against the pipe wall. This arrangement will remove the uncertainty of a flange tap and does not create the inconvenience and uncertainty of drilling into the existing pipe walls.

(e) *Modifying Parshall Flumes:* The Parshall flume will now be calibrated under submerged conditions to verify discontinuity in the discharge/submergence relationship reported by USBR regarding submerged flumes. Then, the Parshall flume will be modified to behave like a long-throated flume. The flume will then be calibrated again to verify that the Parshall flume can indeed be converted into a computable long-throated flume.

(f) *DACL Valve Design:* The new DACL valve will be evaluated for controlling irrigation gate flows to an adjustable constant rate. Testing will evaluate function and durability.

(g) *Books and Book Chapters:* These materials will be completed in cooperation with USBR and NRCS.

(i) *Sediment Resistant Flume:* An idea for a flume system that combines critical-flow flumes and supercritical-flow flumes for measuring heavily sediment-laden flows will be investigated.

COOPERATORS: There are no formal cooperators. Informal arrangements exist with NRCS and USBR. Cooperation with UMA Engineering is reported under another project.

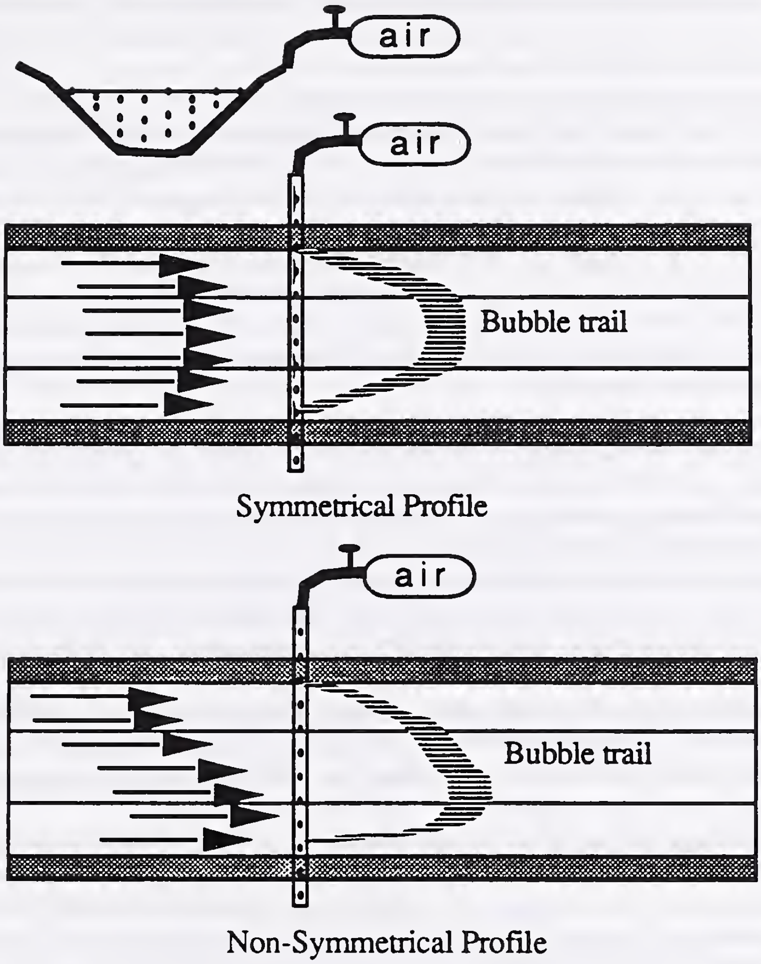

Figure 1. Air bubbles used to check velocity patterns.

MODIFIED LEAF GATES FOR CANAL CONTROL AND FLOW MEASUREMENT

B.T. Wahlin, Civil Engineer; J.A. Replogle, Research Hydraulic Engineer;
and T.S. Strelkoff, Research Hydraulic Engineer

PROBLEM: Recently, overshot gates, or leaf gates as they are sometimes called, are becoming increasingly popular for controlling water levels in open channels (fig. 1). This popularity is partly due to the ability of the gates to limit depth changes associated with flow surges and to the ease with which operators can understand the hydraulic behavior of the gates.

The main purpose of most control gates is to maintain a constant water depth upstream so that orifice-based offtakes, usually located just upstream of the gates, will deliver water at a near-constant rate regardless of the flow rate in the main canal. The control gates themselves can be either orifice-based gates, such as sluice or radial gates, or weir-type gates. Overshot gates combine the best aspects of both sharp-crested weirs and orifice control gates. With overshot gates, the water level can be controlled with the accuracy of a sharp-crested weir, and the gate can be adjusted with the ease of an orifice gate. Overshot gates also require less intuitive operation because a 10-cm drop in gate height corresponds closely to a 10-cm drop in upstream water level.

While water level control is useful, in many cases, operators also need to know the flow rate at each gate. At high gate angles, the overshot gate appears to resemble a sharp-crested weir, while at low gate angles, it looks as if it might behave more like a free overfall.

APPROACH: Kindsvater and Carter (1959) presented a form of the discharge equation for either a fully or partially contracted sharp-crested vertical weir. They considered the effect of the viscous and surface tension forces and introduced an effective discharge coefficient, C_e. The viscous and surface tension forces were accounted for by modifying the width of the weir and the head approaching the weir.

It was hoped that Kindsvater and Carter's discharge equation for sharp-crested weirs would also apply to overshot gates if an appropriate value of C_e were determined accurately with respect to the gate angle. This was done by using the C_e for sharp-crested weirs and modifying Kindsvater and Carter's discharge equation with another discharge coefficient, C_a, that took into account the effects of the gate angle.

When a sharp-crested weir is in a submerged state, the discharge equation must be modified by a drowned flow reduction factor, as suggested by Villemonte (1947). A modified version of Villemonte's drowned flow reduction factor for sharp-crested weirs was used in an attempt to describe the drowned flow reduction factor for an inclined overshot gate.

Extensive laboratory tests were performed on two different leaf gates. The first one was a shop-constructed leaf gate made of 0.635-cm-thick aluminum. The width of the gate was 120 cm, and its length was 61 cm. Because of the structural angle supports and the hinging system used, the gate angles were limited to between 23° and 39°. The second leaf gate studied was a commercial version obtained from UMA Engineering and Armtec, Inc. This leaf gate was constructed of stainless steel 3 mm thick. The length of the gate was 50 cm, and the width was 114 cm. The entire overshot gate was fitted into a glass-sided laboratory channel 123 cm wide and 60 cm deep. The hoisting mechanism used to raise and lower the gate limited the maximum angle that could be achieved to about 65°.

Freefall tests were performed on both of these leaf gates for a variety of different angles and discharges. A discharge coefficient that would allow the sharp-crested weir equation to predict the actual discharge was determined at each gate angle. Next, the Armtec overshot gate was calibrated under a variety of submergence conditions. From these data, the drowned flow reduction factor was determined as a function of the submergence ratio and gate angle.

All flow rates were determined with the laboratory weigh tank system, which is accurate to $\pm 0.1\%$. The hinge joint on the overshot gate leaked only slightly, and it was assumed that these small leaks did not affect the calibration of the gate.

Finally, field tests were performed on full-sized leaf gates in the Imperial Irrigation District in an attempt to verify the laboratory results. The first leaf gate tested had a 1.55-m-long blade. The second leaf gate tested was a blade length of 1.70 m. Both of these gates had a width of 1.63 m. Freefall and submerged tests were performed on these gates using a method similar to that in the laboratory. However, the submerged tests were not performed extensively because of the difficulty in controlling the downstream water surface. All flow rates in the field were measured using a computer-calibrated broad-crested weir that was accurate to within $\pm 2\%$.

FINDINGS: The modified version of Kindsvater and Carter's discharge equation can be used to describe accurately the flow rate in the field of a properly ventilated free-flow leaf gate to within approximately 6.4%. These results are valid for values of h_l/p less than 1.0 (where h_l = measured upstream head and p = gate height) and for gate angles between 16.2° and 63.4°.

The modified version of Villemonte's drowned flow reduction factor was used to predict the field discharges to within an apparent 4% based on limited tests. This empirical relationship is valid for values of h_l/p less than 1.0, for gate angles between 16.2° and 63.4°, and for submergence ratios less than 0.90.

INTERPRETATION: The accuracy of the field experiments on the unsubmerged gate was respectable. The velocity of approach was probably the largest source of error encountered during these experiments. At the field test site, an irregularity in the channel just before the leaf gate caused a contraction in the water surface and visually affected the velocity distribution of the flow. It is hoped that by conditioning the flow, the accuracy of these devices would be improved.

It is surprising that the field submergence tests had a higher degree of accuracy than the free-flow tests because operating weirs under submerged conditions usually reduces their accuracy. It is felt that this result is fortuitous and resulted from the cancellation of different systematic errors. One possible explanation is that in the field, the nappe was allowed to circulate freely after it passed over the crest because there was a sharp drop in the channel bottom just downstream of the gate and the channel expanded from a rectangular control section to a trapezoidal section. These large expansions permitted the tailwater to circulate freely under field conditions as recommended by Villemonte (1947). However, in the laboratory, the tailwater was confined. A confined downstream section introduces areas of low pressure and has the same effect on a submerged weir that an inadequately ventilated nappe has on a free-flow weir. Thus, the Armtec gate tested under the confined laboratory conditions was discharging water at a lower head than if the downstream channel permitted proper circulation of the water. This improper circulation of the water would cause a rise in the value of the drowned flow reduction factor. All the drowned flow reduction factors obtained from the laboratory experiments would then be higher than those obtained from the field experiments. Because the equations developed were based on the laboratory tests, these larger drowned flow reduction factors in the field should improve the apparent accuracy of the discharge equation under submerged conditions.

With a single upstream head measurement, canal operators should be able to use the results of this study to control and measure the flow with an overshot gate under free-flow conditions. The overshot gate can also be used to measure flow under submerged conditions; however, this also requires an accurate measurement of the downstream head. This is usually difficult to do because of the unstable water surface just below the overshot gate. In many cases, downstream depth measurement would not be possible because the flow enters a pipe immediately after the gate. In these cases, the overshot gate cannot be used to measure the discharge under submerged conditions because no downstream depth can be obtained.

FUTURE PLANS: The initial calibration and analysis of the overshot gate are now complete. In the future, these gates will be examined to determine if they can be modified to improve their flow-measuring capabilities. One possible modification would be to convert the leaf gate into an adjustable broad-crested weir as shown in figure 2 (Patent No. 5,156,489). This would greatly improve the discharge characteristics of the gate because the broad-crested weir can be computer-calibrated to within ±2%. Discussions with Armtec, Inc., regarding these modifications have been initiated. Work also has been started on modeling the flow over the gate using potential flow theory and a method similar to that already successfully applied to sharp-crested weirs.

COOPERATORS: UMA Engineering, Imperial Irrigation District, and Armtec, Inc.

REFERENCES: Kindsvater, C.E., and Carter, R.W. (1959). "Discharge Characteristics of Rectangular Thin-Plate Weirs." *Trans. Am. Soc. Civil Engrs.*, Vol. 124, p. 772-822.

Villemonte, J.R. (Dec. 25, 1947). "Submerged Weir Discharge Studies." *Engineering News Record*, p. 866-869.

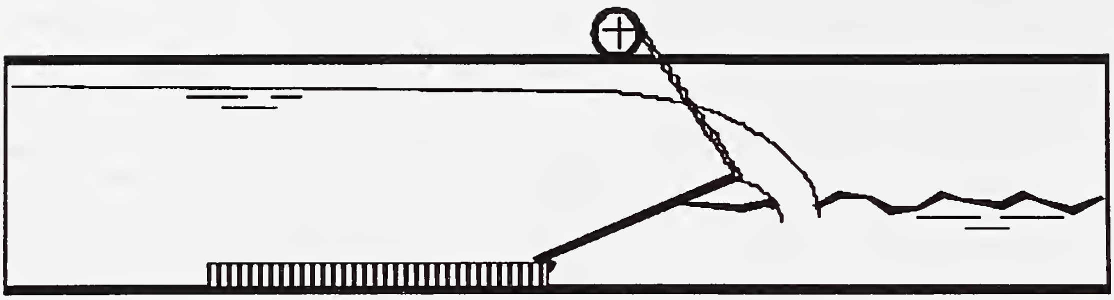

Figure 1. General schematic of an overshot gate.

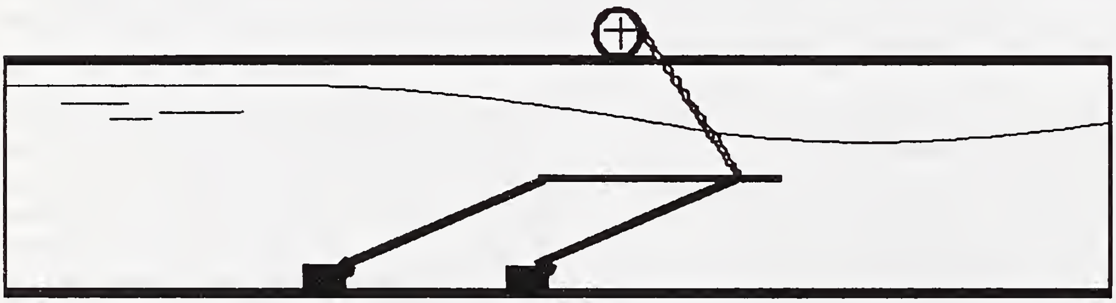

Figure 2. Proposed modification to the overshot gate.

SOFTWARE FOR DESIGN AND CALIBRATION OF LONG-THROATED MEASURING FLUMES

A.J. Clemmens, Supervisory Research Hydraulic Engineer; and J.A. Replogle, Research Hydraulic Engineer

PROBLEM: Flow measurement in irrigated agriculture continues to be a difficult problem. Flow measurements are frequently inaccurate, and structures are often improperly installed. Over the last decade, the long-throated flume has become a very useful tool for improving water measurement in irrigation canals. One of the advantages of this device is that it can be custom designed for each installation, thus better meeting the needs of the measurement site. This can be a disadvantage in that it gives the user so much flexibility that an optimum structure may not be selected.

A computer program, FLUME, has been available since 1987 for the calibration of these flumes. It was not very user-friendly, users frequently made errors in data input, and laboratory personnel spent a significant amount of time answering user questions. Thus there was a need for a more user-friendly flume program that can aid in designing these flumes.

APPROACH: A menu-driven program, FLUME3.0, has been developed to aid in the design and calibration of long-throated flumes for irrigation canals and natural channels. The program includes design procedures developed over the last few years. The user inputs the conditions of the canal and selects the type of contraction desired. Then the program suggests a structure that meets the channel conditions. The program also has graphic data input that shows the flume profile and cross sections so that when the user enters flume dimensions, the changes can be viewed immediately. This should greatly reduce the chance of user error. A database of flume designs and calibration tables is also provided. The project is being sponsored by the International Institute for Land Reclamation and Improvement (ILRI), Wageningen, The Netherlands. A software programmer from Wageningen is under contract to ILRI to write and maintain the program.

FINDINGS: The program and users' manual was released for sale by ILRI in late 1993. Several bugs have been identified, and several are still not yet fixed. The routines for assisting the user in determining tailwater levels continue to produce errors. Fixing one bug seems to produce others. The biggest user complaint is the copy protection software. The program and copy protection software are designed to run on MS-DOS machines. They will not work in DOS windows from OS/2 or from local area networks. The program seems to work well from a DOS shell running in windows. Overall, users seem happy with the program, and the current stock is projected to run out about July 1995. The program is also available from Water Resources Publications in Highlands Ranch, Colorado.

INTERPRETATION: This program should help the transfer of this technology to users in a very effective manner. It will make these flumes an even more valuable tool for improving water management in irrigated agriculture. More thorough debugging is needed to prevent the introduction of new errors into FLUME.

FUTURE PLANS: Plans have been made to revise the current version of FLUME. The program currently can not be used to develop wall gauges. Adding this capability is a high priority for the next upgrade. The following improvements are planned for version 3.1:

1.	Installation	- New menu driven installation program with network and OS/2 capabilities - De-install choice within OPTIONS menu
2.	Wall Gauges	- Ability to print wall gauges to scale on a variety of printers
3.	Improve Graphics	- Upgrade graphics for data entry screens - Upgrade graphics for output graphs
4.	Printer Capabilities	- Upgrade printer capabilities (e.g., selectable paper and font sizes) - Upgrade printer library

Current plans are for the new version to be available by mid-1995.

COOPERATORS: M.G. Bos, International Institute for Land Reclamation and Improvement, and J.M. Groenestein, Groenestein and Borst, Ltd.

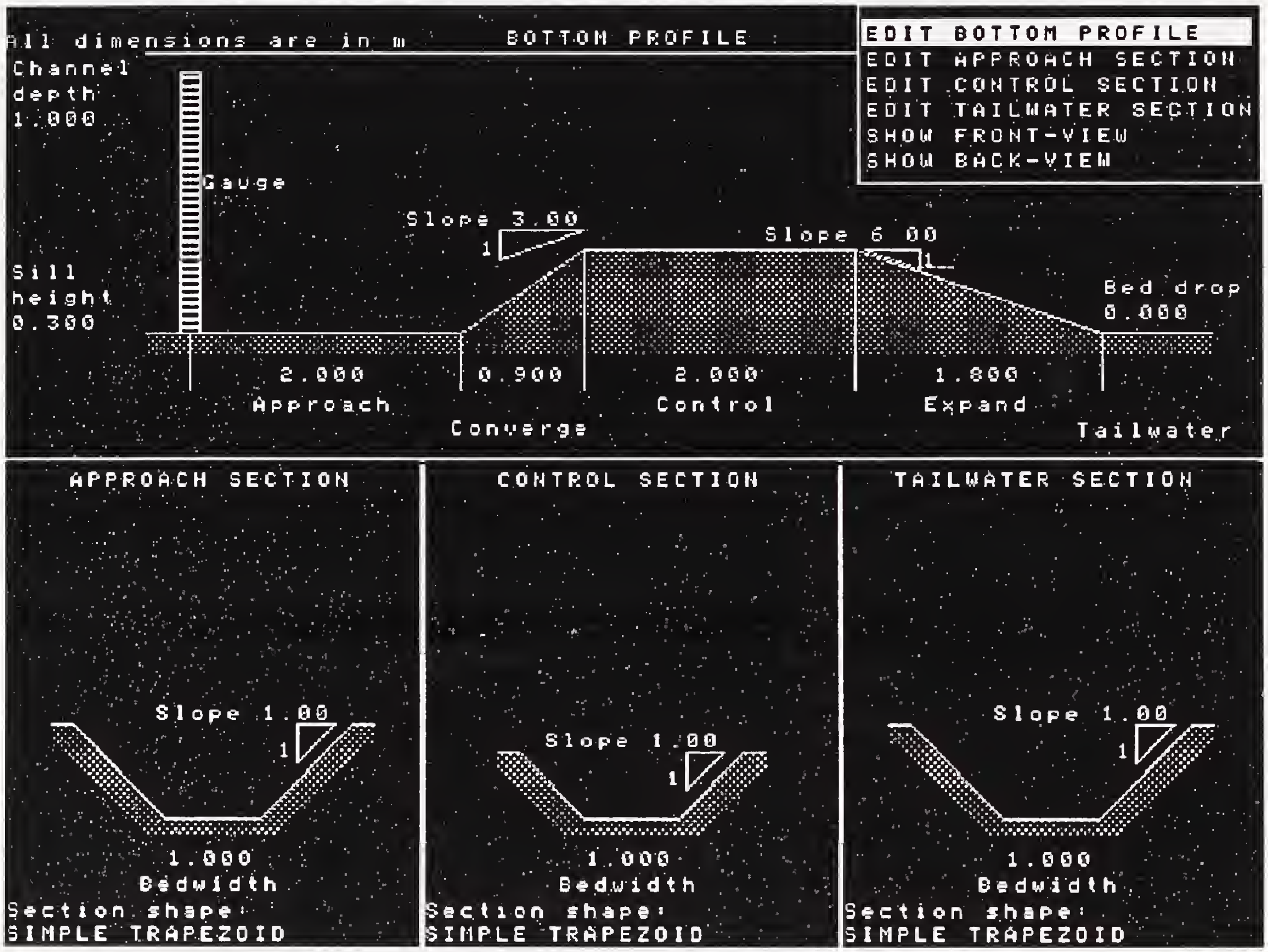

Figure 1. Graphics data entry screen for default flume.

```
User : Clemmens/Bos/Replogle              Report made on: November 20, 1992
Flume: Phoenix , example structure used in manual                 Version  3
                       EVALUATION OF FLUME DESIGN

GENERAL RESULT : Design is acceptable.     2 lines of error/warning text.
                Headloss design aims are not fully met

             EVALUATION OF FLUME DESIGN FOR EACH DESIGN CRITERION

Ok.    Freeboard at Qmax.:    Actual=0.356 m    Minimum=0.094 m

Ok.    Head at Qmax.:         Actual=0.469 m    Minimum for accuracy=0.235 m

Ok.    Head at Qmin.:         Actual=0.100 m    Minimum for accuracy=0.099 m

Ok.    Tailwaterdepth Qmax.: Actual=0.844 m    Maximum allowed=0.858 m

Ok.    Tailwaterdepth Qmin.: Actual=0.109 m    Maximum allowed=0.507 m

Ok.    Froude nr. at Qmax.:   Actual=0.315      Maximum= 0.500

                    ADVICE, WARNINGS AND ERROR MESSAGES

Headloss design aims are not met.
Too much contraction in initial control section shape.

                           RESULTING STRUCTURE

Sill Height = 0.425 m
CONTROL SECTION DATA
Section shape = SIMPLE TRAPEZOID
Bedwidth = 1.850 m             Channel side slope =  1.00:1

                             DESIGN STRATEGY

Headloss design aim:  Minimize headloss
Contraction change strategy:  Vary height of sill

                             DESIGN CRITERIA

Type of structure: Stationary crest.
Freeboard design criterion: Percentage of head over sill = 20 %
Allowable discharge measurement errors for a single measurement:
  At minimum discharge:  8.00 %.    At maximum discharge:  4.00 %
Head detection method:  Staff in still Fr=0.2  Readout precision: 0.005000 m
Design discharges and associated tailwater levels:
  Minimum discharge =  0.100 m3/s    Minimum tailwater level=  0.109 m
  Maximum discharge=  1.300 m3/s    Maximum tailwater level=  0.844 m
  Values derived using: 2 Q-H measurements
== Use cursor keys, PgUp, PgDn, etc., to view whole text==
```

Figure 2. FLUME design results screen.

IRRIGATION CANAL AUTOMATION

A.J. Clemmens, Supervisory Research Hydraulic Engineer; and
R.J. Strand, Computer Programmer

PROBLEM: Surface-irrigation efficiency can most easily achieve high levels when the supply canals have been designed and are operated in a way to supply the necessary water at the right time to each of the users of the resource. In present systems, meeting the canal-delivery requirements for efficient demand irrigation is not assured. The operation of gates and pumps in a canal system produces waves, which transmit the effects of these operations throughout the system. As irrigation canal systems become more responsive to farm demands, changes in flow occur more frequently, causing unsteady flow throughout the system. Even large canal systems with rigid delivery policies that supposedly operate under steady flow often experience unsteady flow for long periods of time.

Most canal systems operate with manual upstream control. A constant water level at each offtake is maintained to keep delivery flow rates constant. The disadvantage of this method of operation is that all flow errors culminate at the tail end of the system. In large canals, supervisory control systems are used to adjust volumes in intermediate pools to keep differences between inflow and outflow more evenly distributed in the system, or to simply store the water until a balance is achieved. Smaller canals with insufficient storage need more precise downstream control methods than are currently available. Development of improved canal control methods requires convenient simulation of unsteady flow by computer. Many computer models of unsteady canal flow have been built in the last twenty years, some complex and expensive, designed to model very complicated systems. Only recently have these programs been geared toward canal automation so that simulation of control algorithms could be efficiently made.

The objective of this research is to develop tools for the improved operation of irrigation canal networks, more specifically to improve canal control algorithms, improve capabilities of unsteady flow simulation programs to allow testing of algorithms, and to test improved control algorithms in the field.

APPROACH: Advances in control engineering have not been fully applied to irrigation canal downstream control. A few downstream control techniques are in use, but they have not been tested fully to determine their limitations. To aid in the evaluation of existing techniques and development of new ones, data were collected on several canals that may prove difficult to control with existing methods. Further, we will collaborate with canal control experts to assess various methods for automatic feedback control and assist in the implementation of these methods on these test canals. Canals within the Maricopa-Stanfield Irrigation and Drainage District (MSIDD) will be studied because they have the hardware available to control automatically gates at all check structures within lateral canals. The first step in this research program will be to test these algorithms with an unsteady-flow simulation model.

The performance of automatic feedback canal control algorithms is influenced by the general properties of the canal, the nature of demand changes (and how well they are known ahead of time), and the properties of the control algorithm (and how well it is suited to the canal). Feedforward (anticipatory) canal control algorithms are influenced by the level of knowledge of specific canal parameters and the extent of unanticipated disturbances. The approach taken here will be to combine these two kinds of control in order to utilize the advantages of each where possible.

The general approach is to find the simplest controller that will be suitable for a particular canal. Two related projects deal with: 1) the properties of a canal that influence control response, and 2) the accommodation of anticipated flow changes (e.g., routing).

FINDINGS: A canal control example was developed based on the field data collected during 1992 on MSIDD's WM canal. The layout for this canal is shown in figure 1. The objective of the controller in this example is to adjust canal inflow and check gates to provide a constant water level upstream from each gate, which implies a constant discharge to farm offtakes. The example canal was tested with several types of simple PI controllers.

With feedback control only (no anticipation), simple PI controllers (including CARDD) performed poorly. Better control was obtained when discharge was changed by the controller rather than gate position. In essence, this tends to keep errors from being transmitted downstream from a disturbance. Significantly better control resulted when changes in flow rate were anticipated (i.e., routed through the system from the canal head). Some conflicts between the feedforward and feedback actions occurred. figures 2-4 show results of various control strategies on the WM canal (from simulation). The test scenario is a large change in offtake discharge near the tail end of the canal (at

check 7) and a feedback control system responding to keep the level at the downstream end of each pool constant. figure 2 shows the variation in discharge for offtakes at the upper end of the canal (at checks 1, 2 and 4) when a simple PI controller is employed. figure 3 shows the same offtake discharges for a PI controller that also transmits requests for flow changes to gates upstream (still strictly feedback). figure 4 shows the same when anticipation of offtake discharges is included. In the first two figures, the change occurs downstream at 10 min., while for figure 4 it occurs at 2 hours. Note that even with anticipation, control will not be perfect because of wave dispersion, imperfect prediction of wave travel times, and errors in gate settings.

The main problem with simple PI controllers is the delay time. Adding predictive capabilities to simple PI controllers (e.g., a Smith predictor) is expected to improve control when feedback alone is used. Such controllers have been called PIR (Proportional, Integral, Retard). The degree of improvement is not yet known and will vary depending upon canal specifics. Predictive control should also eliminate the conflict between the feedforward and feedback actions, since the influence of both can be predicted. Current PIR methods handle the feedforward independently of the PIR loop (i.e., they are not included in the prediction).

Work has begun, in conjunction with an ASCE task committee, on determining methods for quantifying canal properties that suggest their suitability for various automation methods. Three subgroups have been working on classification of existing algorithms, test cases for comparing algorithms, and canal hydraulic properties that influence automation potential or suitability.

Work began on adapting the gate hardware and supervisory control software at MSIDD to allow it to be interfaced with the automation software. MSIDD is doing the hardware modifications, while CAIDD (Central Arizona Irrigation and Drainage District) personnel are doing the software revisions.

A cooperative agreement was made with California Polytechnic University (CPU) to adapt the CANALCAD program to the needs of canal automation testing at MSIDD.

Testing of optimal control with CANALCAD on the MSIDD Santa Rosa Canal was also continued during 1994.

INTERPRETATION: The performance of feedback level-control algorithms can be improved by imbedding gate hydraulics algorithms into the controller, e.g., by specifying the control signal as a change in flow rate rather than gate position. The suitability of feedback controllers depends upon canal hydraulics and the nature of changes in demand. For many situations of interest, significant improvement in control can be obtained by anticipation of demand changes, even if imperfectly known.

FUTURE PLANS: Field testing of several control algorithms will be conducted during 1995. Two PhD students from the Delft University of Technology will visit the USWCL for 3 months during 1995 to perform initial tests on MSIDD's WM canal. Plans for the remainder of the year will depend on the results of these tests. Preliminary plans are to work with MSIDD to integrate the water ordering with the canal automation algorithms so that projected changes in water demands can be used to improve control. Then real-time automation over an extended period can be tested on this canal. Testing of optimal control on the Santa Rosa canal also will continue. A lateral canal with properties somewhat different from the WM canal will be selected for future analysis and testing of control algorithms.

COOPERATORS: Gary Sloan, MSIDD; Ken Taylor, CAIDD; Pascal Kosuth, CEMAGREF; Charles Burt and John Parrish, CPU; Wytze Schuurmans and Jan Schuurmans, Delft UT; Mohan Reddy, University of Wyoming.

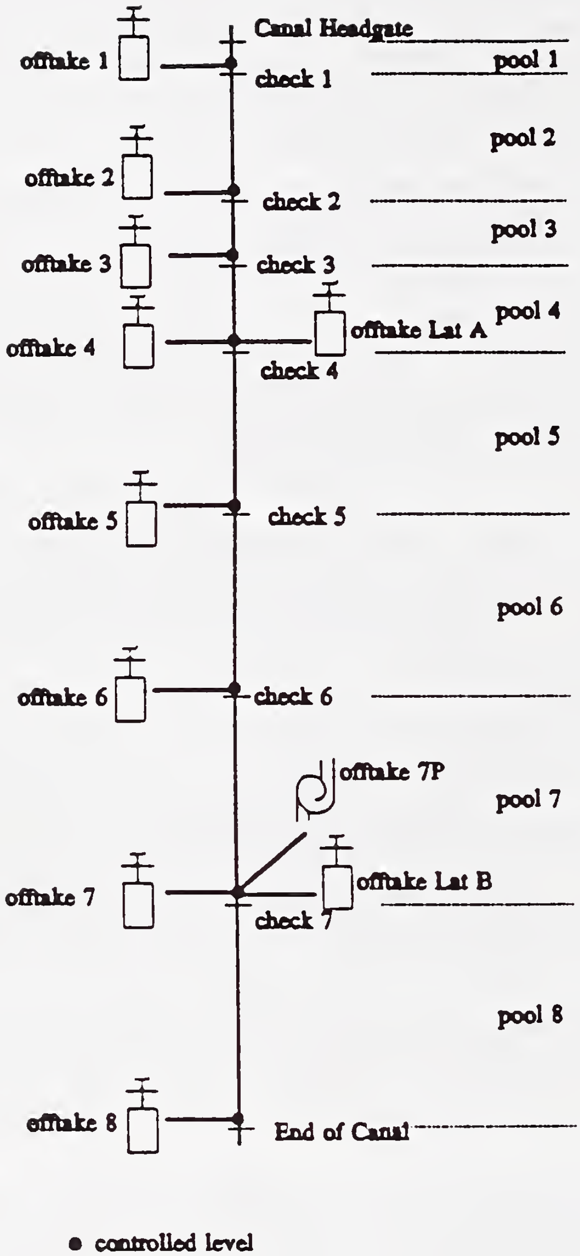

Figure 1. Plan view of WM lateral canal.

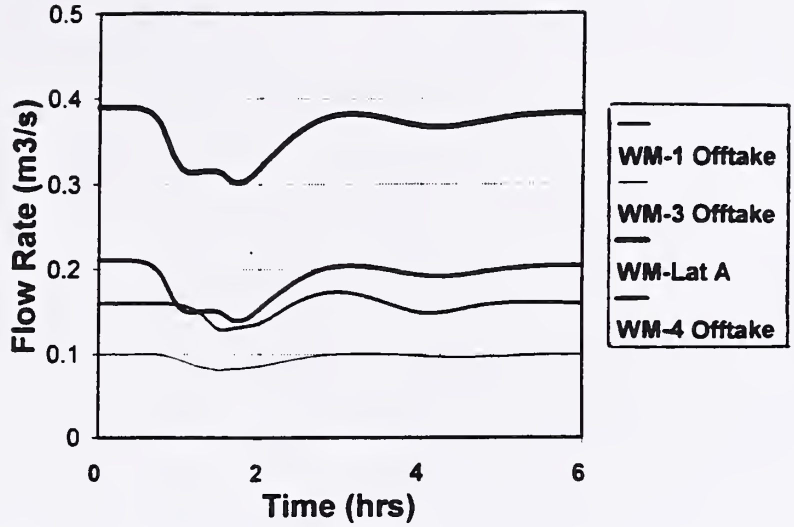

Figure 2. Example offtake flow changes with simple PI controller (discharge-based).

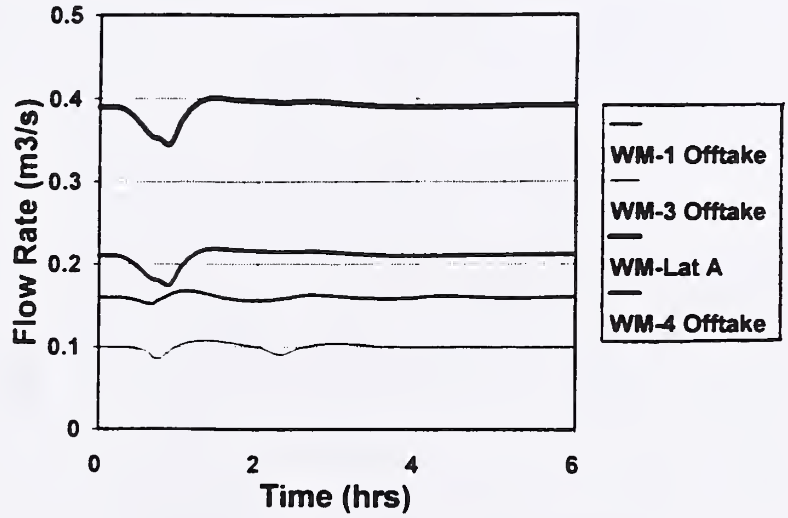

Figure 3. Example offtake flow changes with PI controller (discharge-based) and upstream communication of downstream demand (still feedback alone).

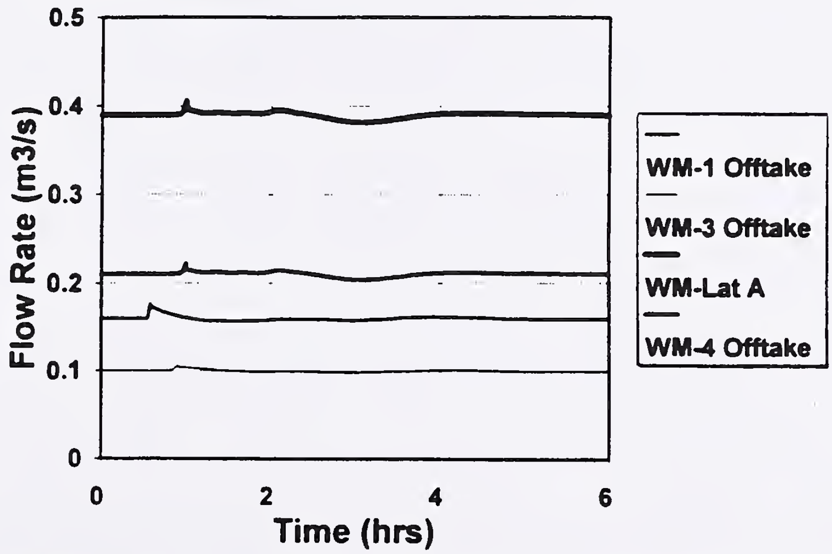

Figure 4. Example offtake flow changes with PI controller (discharge-based) and prescheduled gate changes (i.e., feedforward).

PROTECTION OF GROUNDWATER QUALITY

WATER REUSE AND GROUNDWATER

H. Bouwer, Research Hydraulic Engineer

PROBLEM: The aim of this research is to develop technology for optimum water reuse and the role that soil-aquifer treatment can play in the potable and nonpotable use of sewage effluent. Increasing populations and finite water resources demand water reuse, as do increasingly stringent treatment requirements for discharge of sewage effluent into surface water. In Third World countries, simple, low-tech methods must be used. Such methods will be applied to demonstration projects in the Middle East and North Africa under the Middle East Peace Initiative.

APPROACH: Technology based on previous research at the USWCL and more recent research are applied to new and existing groundwater recharge and water reuse projects. Main purposes of the projects range from protecting water quality and aquatic life in surface water to reuse of sewage effluent for nonpotable (mostly urban and agricultural irrigation) and potable purposes.

Cooperative research has been initiated with The University of Arizona to manage clogging layers for optimum benefits in infiltration systems for groundwater recharge and soil-aquifer treatment where clogging layers are not wanted, and in constructed wetlands, aquaculture ponds, and animal waste lagoons where clogging layers are wanted. Both hydraulic and water quality aspects are considered. New research is being developed on novel approaches, such as seepage trenches and techniques for well or trench recharge with sewage effluent without reverse osmosis or other membrane filtration as pretreatment.

FINDINGS: Initial field tests show that the area for a large Phoenix project is suitable for recharge with infiltration basins. Current research is aimed at sustainability of soil-aquifer treatment and fate of recalcitrant organic compounds. Tests with experimental recharge shafts north of Scottsdale, Arizona, showed that recharge rates continued to be within the range predicted on the basis of reverse augerhole theory.

INTERPRETATION: Results will be applied to existing and planned groundwater recharge and soil-aquifer treatment systems. Research proposals for funding by research foundations have been prepared. The National Academy of Sciences report on groundwater recharge with low quality water has been completed. Various national and international conferences on groundwater recharge, soil aquifer treatment, and water reuse were participated in. Other national and international conferences are being planned and prepared.

FUTURE PLANS: Future plans primarily consist of initiating and coordinating research on groundwater recharge and water reuse and responding to requests to write, speak, and advise.

PHYSICAL, CHEMICAL AND BIOLOGICAL CHARACTERISTICS OF A SCHMUTZDECKE: EFFECTS OF SEEPAGE AND WATER TREATMENT IN WASTEWATER DISPOSAL FACILITIES

H. Bouwer, Research Hydraulic Engineer

PROBLEM: Soil clogging occurs during artificial recharge and effluent disposal operations. Reduced infiltration and consequent ponding are largely attributed to development of a slime layer, or "schmutzdecke." The objectives of this project are to determine (1) the physical, chemical, and biological processes occurring in the schmutzdecke, (2) the improvement of water quality after it has moved through the schmutzdecke (for example, the effect of the schmutzdecke on speciation of dissolved organic carbon), (3) how schmutzdecke should be managed for specific needs (in particular, to evaluate how the schmutzdecke affects the flow of essential nutrients: nitrogen, phosphorous, and potassium), and (4) how the schmutzdecke of infiltration affects the hydraulics.

APPROACH: During the second year of this project, nine soil columns (3.25" i.d. x 9.0" length) have been utilized for study of surface clogging layers. All columns are packed with soils obtained from the Sweetwater US&R Facility. Filtered primary, dechlorinated secondary, ozonated secondary, and tertiary effluents have been applied to the columns in alternating wet/dry cycles. Samples are collected from column influent and effluent for measurement of dissolved organic carbon (DOC), UV absorbance at 254 nm (UV254), trihalomethane formation potential (THMFP), pathogens, and nitrogen species. Ozonation of secondary effluent was performed at a transfer ratio of 1:1 (ozone to organic carbon). Biodegradable dissolved organic carbon (BDOC) tests have been used to determine the fraction of DOC potentially degradable by aerobic bacteria over a five-day period. A control column received sodium azide-amended secondary effluent for the purpose of distinguishing biological versus nonbiological removals of organics through schmutzdecke. Two additional columns, receiving secondary and tertiary effluents, have been operated in parallel for subsequent use in compressibility studies. A separate compressibility study is being conducted at Arizona State University (ASU).

FINDINGS AND INTERPRETATION: Removal of Organics--Studies using secondary and tertiary effluents with the Sweetwater soil are now finished, following completion of 15-21 cycles of operation. Infiltration rates were reduced from 60 ft/day to about 1 ft/day over the course of three wet cycles (each cycle 3-7 days in length). Bromide tracer tests indicated that column detention time was 1 hour at an infiltration rate of 2.3 ft/day. Results reported here are based on column operation during the last five - eight cycles of operation, considered most representative of mature schmutzdecke development.

Through-column removals of DOC averaged 22%, irrespective of pretreatment level. Removal of UV254 averaged 12%, using secondary effluent. Removals in the control column averaged 6 and 1% for DOC and UV254, respectively, suggesting that aerobic biological activity was responsible for the bulk of organics removal through schmutzdecke. Pre-ozonation of secondary effluent at a mass rate of 1:1 (ozone to carbon) did not significantly increase the degradable fractions of DOC or THMFP (represented by the fraction of organics within the <500 dalton size) by schmutzdecke (table 1). BDOC tests indicated that the fraction of organics amenable to aerobic degradation was not enhanced following ozonation. Moreover, the observation that post-column and post-BDOC concentrations of THMFP were similar (table 1) supports the observation that ozonation did little to enhance THMFP removal. Ozonation reduced UV254.

Two columns receiving filtered primary effluent have completed seven cycles of operation. Suspended solids are removed from primary effluent using a sand filter. Through-column reduction of DOC and UV254 was minimal at infiltration rates ranging from 25 ft/day initially to 3 ft/day after five days of operation. Dissolved oxygen profiles taken on these columns indicate that little if any oxygen is present below a soil depth of 10 mm, thus precluding aerobic biological activity. Matric potential progressively decreases during wet cycles within the top 10 mm of soil, reflecting surface clogging development. BDOC tests using primary effluent show that >60% of DOC is removed within the first 15 hours under aerobic conditions.

Compressibility Studies--A full characterization of the five soil types selected for this study have been made. A material properties report documenting the full details of this work has been completed and is available from ASU. In addition, algae have been identified for the soils and effluents from the 91st Avenue Water Treatment Plant. Several species of diatoms (motile and nonmotile) and filamentous algae have been identified.

FUTURE PLANS: Future studies will include an examination of the fate of specific classes of organic compounds (e.g., humic acids, fulvic acids, hydrophobics, and chloroacetic acids) through schmutzdecke. Dissolved oxygen, redox potentials, nitrogen species, and matric potential measurements will be monitored with depth. In addition, columns receiving filtered primary effluent will be monitored for phosphate and potassium. Additional columns receiving filtered primary effluent will be operated at constant hydraulic loading rates so that ponded conditions are prevented, thereby maintaining significant oxygen levels through soil profiles.

Future work on nitrogen transformations will concern (1) the pulse of nitrate observed in field studies at the beginning of a wet cycle, (2) the extent of denitrification, and (3) maximization of nitrate removal through variation of operational parameters. Comparison of nitrogen speciation and DOC for primary vs. secondary effluent treatments will determine if a pattern of nitrate removal with increasing C:N ratio can be documented.

To examine the influence of the clogging layer on infiltration rate, the various components of schmutzdecke will be subjected to one-dimensional consolidation testing. These tests involve the application of a series of increasing vertical loads to the specimen and observing time-deformation data during each load increment. The results can be used to quantify the compressibility and hydraulic conductivity of the materials. Although traditionally applied to soils, the test apparatus and procedures have been modified to allow the study of the more compressible components such as the algae. The loads will be applied through two different methods in an attempt to more closely simulate field behavior. The equipment for these tests has been designed and constructed. The test procedures have been developed, and routine testing is underway.

COOPERATORS: M. Conklin, Assistant Professor; L.G. Wilson, Hydrologist; R. Arnold, Associate Professor; C.P. Gerba, Professor; K. Lansey, Assistant Professor; D. Quanrud, P. Chipello, P. Soto-Navarro, J. Hillman, and K. Miles, Research Assistants, The University of Arizona; and S. Houston, Associate Professor; P. Fox, Assistant Professor; and P. Duryea, Research Associate; Arizona State University

Table 1. Water quality characteristics for column influent, column effluent, and post-BDOC fractions of secondary and ozonated secondary effluents.

Parameter	Column influent	Column effluent	Post BDOC
	Secondary		
DOC(mg/L)	11.5	8.3	5.3
UV254(/cm)	0.169	0.130	0.070
THMFP (ug/L)	372	326	273
	Ozonated Secondary		
DOC(mg/L)	13.1	8.6	5.1
UV254 (/cm)	0.084	0.076	0.068
THMFP (ug/L)	322	283	269

NITROGEN FERTILIZER AND WATER TRANSPORT UNDER 100% IRRIGATION EFFICIENCY

R.C. Rice, Agricultural Engineer; F.J. Adamsen, Soil Scientist;
D.J. Hunsaker, Agricultural Engineer; H. Bouwer, Research Hydraulic Engineer;
and F.S. Nakayama, Research Chemist

PROBLEM: Nitrate is the most common groundwater pollutant observed under irrigated crop production. The rising trend in nitrate levels of groundwater suggests that nitrogen fertilizers frequently are being transported beyond the beyond the root zone. Improving management practices in irrigated agriculture may lead to better control of nitrogen contamination of the groundwater. Nitrogen management can result in less nitrate available in the lower root zone. Using feedback techniques such as soil and crop nitrogen status and more frequent fertilizer applications with smaller application rates are suggested as better management practices. Crop leaching requirements could be met when crops are not being grown and when most of the applied nutrients have been used by the crop. Irrigating at 100% irrigation efficiency may result in less deep percolation. Previous studies indicate that 100% irrigation efficiency during the growing season limited the transport of nitrogen to the vadose zone. However, preferential flow and spatial variability may cause water and nutrient losses from the root zone even under ideal management conditions. Current technology and state of knowledge of downward movement of agricultural chemicals to groundwater are inadequate because they do not consider spatial variability and preferential flow and because the actual processes of physical, chemical, and biological attenuations are not adequately understood.

The objective of this study is to determine the movement of water and nitrogen fertilizer in the soil profile when irrigating at 100% irrigation efficiency and to develop associated Best Management Practices (BMPs) to protect the quality of underlying groundwater.

APPROACH: Studies on cotton and wheat grown using level basin flood irrigation were continued in 1994. The experimental design was a complete randomized block with six fertilizer-water application treatments and three replications. Each experimental plot was 108 m^2. Micro-plots were established in each plot and fertilized with nitrogen-15-labeled fertilizer. A different conservative tracer was applied with each fertilizer application. Water movement in the soil profile was characterized with soil water content and tracer analysis. Evapotranspiration was estimated from soil water depletion data and energy balance techniques using meteorological data collected at the site.

In experimental treatments 1) irrigation and fertilizer applications are scheduled according to current farm practices with 100% irrigation efficiency, with 80% irrigation efficiency, and with 20% deficit irrigation; 2) irrigation-applied fertilizer applications are scheduled according to residual soil, petiole NO_3-N feedback and with 100% irrigation efficiency, with 80% irrigation efficiency, and with 20% deficit irrigation.

FINDINGS: Nitrate concentrations in the soil profile for wheat are shown in figure 1 for the different treatments. The total applied nitrogen fertilizer in the soil after harvest and the pre-plant nitrate nitrogen are also shown. The profile of applied nitrogen as determined from ^{15}N analysis is greatest at 30 cm and decreases with depth. Some of the applied nitrogen did move beyond the 270- cm sampling range. The nitrate concentrations were greatest near the surface and decreased to low values at 60 to 90 cm. A nitrate peak occurred at 150 cm in the BMP treatments and at 150 to 180 cm in the standard treatments. The source of the nitrate peak was residual nitrogen in the profile and leached by the early irrigations. At 100% irrigation efficiency and deficit irrigation for both the standard and BMP treatments, less nitrate was leached below 100 cm. There was more NO_3-N in the profile below the root zone at 80% efficiency, indicating more leaching. The deficit irrigation treatment had the least NO_3-N below the root zone. The amount of nitrate in the profile is also illustrated in table 1 where the accumulated nitrate is shown for the different treatments at harvest (June) and 80 days later (August). The total NO_3-N is consistently higher than the applied nitrogen below 100 cm. The root zone was about 140 cm for the wheat crop. Nitrogen below this depth would not be available to the crop and subject to deep percolation. The total nitrate below the root zone was greatest in the standard treatments because of higher application rates. The BMP treatments showed lower levels of nitrate in the deficit irrigation and 100% efficiency treatments. At 80% efficiency, however, the BMP treatment was similar to the standard treatment. Nitrate levels increased in the profile after about 80 days of fallow. Increased levels of NO_3-N in the top 180 cm occurred in all treatments with the largest increase occurring in the top 30-60 cm. Mineralization of organic nitrogen was the probable source.

INTERPRETATION: Management practices such as applying fertilizer at more frequent intervals and irrigating at 100% efficiency during the growing season may result in less leaching of the nitrate below the root zone. Nitrate levels increase during the fallow period probably from mineralization of organic nitrogen. Existing nitrate in the soil profile at the start of the growing season may be leached when nitrate is moved below the effective root zone from early irrigations before the crop is established. Best management practices need to consider pre-plant soil nitrogen status, timing of fertilizer and irrigation applications, and build-up of nitrate during the non-crop season.

FUTURE PLANS: Nitrate leaching under different irrigation methods (drip or sprinkler) will be investigated. Fertilizer application methods such as chemigation (applying with irrigation water), broadcast, side dressing, and foliar spray will be investigated.

COOPERATORS: J.E. Watson, University of Arizona, Maricopa Agricultural Center

Table 1. Accumulated nitrate-N in profile for different irrigation and fertilizer management treatments after harvest (June) and August.

	Standard			BMP		
	kg/ha					
Depth cm	20% Deficit	100% Efficiency	80% Efficiency	20% Deficit	100% Efficiency	80% Efficiency
			Total soil nitrate-N in June			
30	32	44	32	39	42	40
60	43	59	43	49	49	50
90	58	69	57	55	51	55
120	86	88	74	69	62	71
150	118	118	93	84	83	97
180	138	153	108	93	97	119
210	148	172	126	100	105	137
240	155	192	140	109	113	157
270	163	216	154	120	128	179
			Total soil nitrate-N in August			
30	70	63	61	47	66	68
60	91	80	91	67	85	87
90	98	90	103	72	90	93
120	118	107	122	81	105	102
150	144	131	135	89	123	109
180	169	153	141	99	138	116
210	178	164	147	104	144	120
240	192	177	158	111	152	137
270	202	193	172	132	165	159

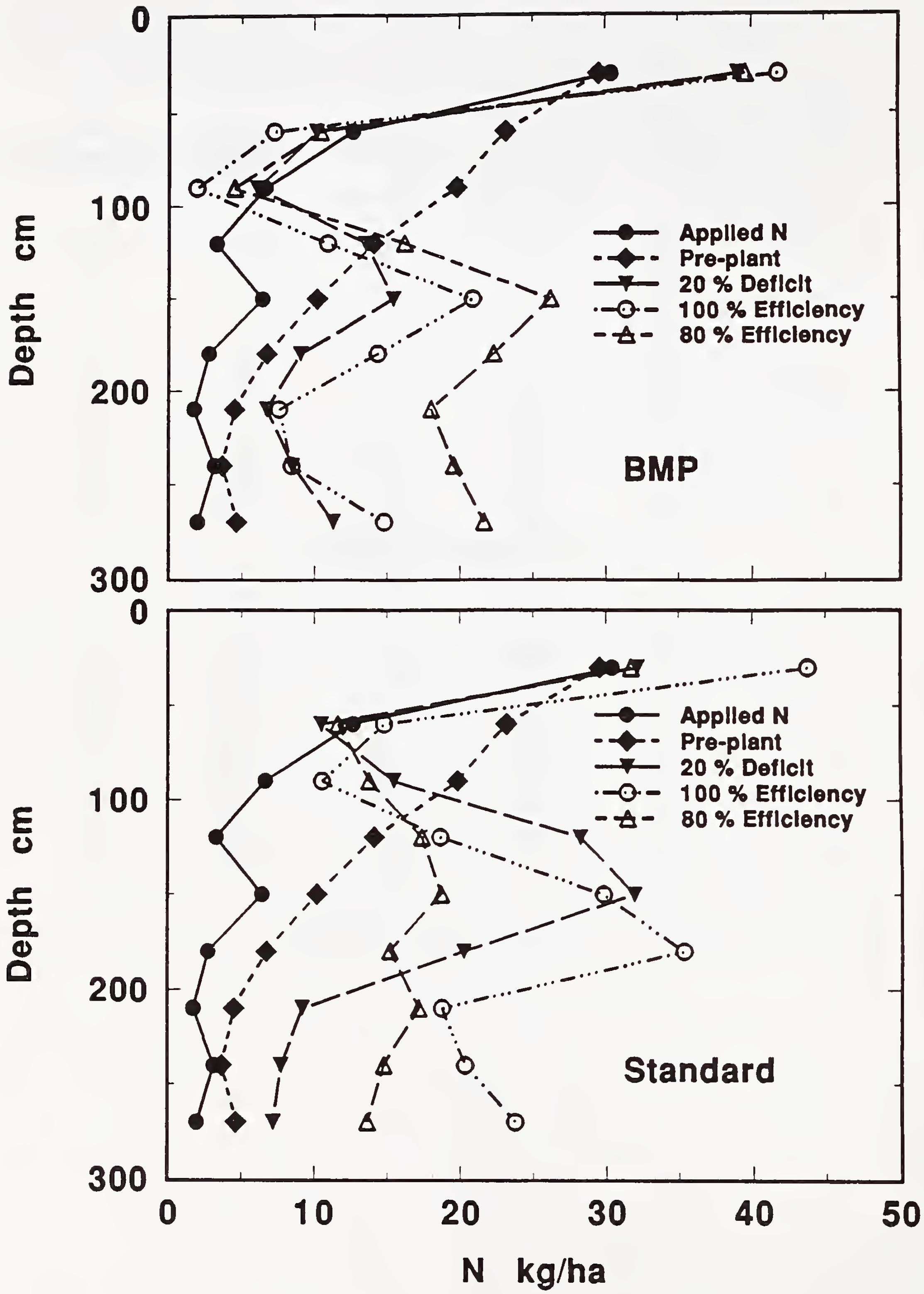

Figure 1. Total applied nitrogen, pre-plant nitrate, and nitrate concentrations for the different treatments.

NITROGEN BUDGETS OF IRRIGATED CROPS USING NITROGEN-15 UNDER HIGH EFFICIENCY IRRIGATION

F.J. Adamsen, Soil Scientist; R.C. Rice, Agricultural Engineer; F.S. Nakayama, Research Chemist; D.J. Hunsaker, Agricultural Engineer; and H. Bouwer, Research Hydraulic Engineer

PROBLEM: Nitrate is the pollutant most commonly found in groundwater. The contribution of nitrate to groundwater pollution carried by deep percolating irrigation water could be reduced or eliminated by the development of existing and new technologies. This requires a better understanding of the total nitrogen required by the crops produced and the timing of nitrogen uptake as well as chemical and water transport in the soil environment. Careful timing of fertilizer applications and prudent operation of irrigation systems to reduce the amount of water lost below the rooting zone can reduce the movement of water and chemicals to groundwater. Theoretically, irrigating at 100% efficiency and carefully controlling fertilizer amounts and timing of applications should lead to no deep percolation and no fertilizer leaching losses. Crop leaching requirements could be met when soil nitrate levels were lowest. However, because of spatial variability, preferential flow, and incomplete uptake of nitrogen by the crop, 100% irrigation efficiency and optimum nitrogen management may still produce some deep percolation and transport of nitrate to groundwater.

APPROACH: Research is being conducted through a series of experiments to evaluate irrigation efficiency theory and nitrogen management practices. Wheat was grown in the 1991-1992, 1992-1993 and 1993-1994 seasons using level-basin flood irrigation. Wheat and cotton were planted in 1993 and 1994. Future experiments will use other irrigation methods such as drip and sprinkler irrigation. The experimental design is a complete randomized block with six fertilizer-water application treatments and three replications. Experimental plots were approximately 81 m^2 in size in 1991 and 108 m^2 in 1992, 1993 and 1994. A different conservative tracer was applied with each irrigation, and nitrogen-15 tagged fertilizer was applied to three micro-plots in each main plot in 1991 and two micro-plots in 1992, 1993 and 1994. Micro-plots were approximate 1 m^2 in 1991 and 1992 and 1.5 m^2 in 1993 and 1994. This allows a complete water and nitrogen balance, including the amount of nitrogen removed with the harvested crop, percolation losses, and volatile losses by difference. The nitrogen status of the crop was determined by tissue analyses and leaf chlorophyll content with a chlorophyll meter. Chlorophyll measurements may allow a rapid, cost effective method for determining the nitrogen status of a crop in real time and may be useful in determining the amount and timing of fertilizer nitrogen. Water movement in the soil profile is characterized by soil water content and tracer analysis. Evapotranspiration is estimated from energy balance techniques.

Experimental treatments include 1) a "standard" fertilizer and irrigation management procedure in which irrigation and fertilizer applications are scheduled according to current farm practice with irrigation amount as 100% of estimated evapotranspiration (ET), 2) same as treatment 1 except with 120% of ET, 3) same as treatment 1 except with a deficit irrigation equivalent to 80% ET, 4) scheduling irrigation water-applied fertilizer (chemigation) according to residual soil, petiole NO_3-N feedback, and leaf chlorophyll content with irrigation amount as 100% of ET, 5) same as treatment 4 except with 120% of ET, and 6) same as treatment 4 except with a deficit irrigation equivalent to 80% ET.

FINDINGS: In 1993-1994 wheat, all treatments received 58 kg ha^{-1} of N broadcast at planting as $(NH_4)_2SO_4$ and an additional 87 kg ha^{-1} of N was applied. In the standard treatment, the additional nitrogen was applied in one application while in the BMP treatment, the additional N was applied in two applications. Rainfall in the winter of 1993-1994 was near normal, and as a result, there were differences in water application throughout the growing season.

Overall, grain yields averaged over 3068 kg ha^{-1} which was lower than 1992-1993 yields (table 1). Yields from BMP plots were comparable to those from the standard fertilizer treatment. Water did not appear to affect grain yields.

In 1994 cotton, the standard fertilizer treatment was 113 kg ha^{-1} applied broadcast at planting as $(NH_4)_2SO_4$ and an additional 85 kg ha^{-1} applied in the irrigation water. The BMP nitrogen treatment was 57 kg ha^{-1} applied broadcast at planting and an additional 96 kg ha^{-1} applied in two applications in the irrigation water. Rainfall for the summer of 1994 was below normal. The irrigation treatments received differing amounts of irrigation water throughout the entire growing season.

Lint and seed yields increased as water increased (tables 2 and 3). One of the benzoic acid tracers applied with the fertilizer affected the cotton. The leaves were misshapen and early bolls were aborted. Bolls that did mature did not open properly. The lint that was produced will be analyzed for quality to determine how the tracer affected plant development.

Results of nitrogen-15 analyses of wheat from the 1991-1992 crop year show that approximately 20% of the applied fertilizer was recovered in the grain and straw (table 4). The portion of fertilizer-N in the straw was lower than the portion in the grain, which was a response to the split application of fertilizer. Nitrogen-15 analyses of soil samples taken after harvest showed that small amounts of fertilizer nitrogen moved below the root zone in all treatments. In the standard treatment, 30% of the fertilizer was unaccounted for in the soil or crop and in the BMP treatments, approximately 10% of the fertilizer-N was unaccounted for (table 4). While there is some evidence of leaching losses in all of the treatments (figs. 1 and 2) most of the unaccounted for N was probably lost through gaseous mechanisms.

INTERPRETATION: The amount of nitrogen application in the BMP treatment was increased in the 1993-1994 crop year over the previous years, and this eliminated the response to fertilizer treatment, but wheat still did not respond to water treatment even in a normal year which suggests that the estimates of water requirement may need to be revised. The apparent lack of response by wheat to irrigation amounts is promising because nitrate can be retained in the root zone by controlling irrigation. Cotton, on the other hand, did respond to water in 1994 as in other years. Cotton yields decreased with decreasing water application but were not affected by the fertilizer program used. This suggests that reducing water inputs may not be an effective method of reducing nitrate movement but improved timing of both water and nitrogen, i.e., more intensive management, may be needed to control nitrate movement below the root zone in cotton.

Nitrogen-15 data show that water and fertilizer derived nitrogen are moving below the root zone in all treatments. The BMP fertilizer treatments retained a higher percentage of the fertilizer-N. In the standard treatment, gaseous losses of nitrogen appear to have been important. These losses were probably a combination of denitrification and ammonia volatilization. Improved water management appears to reduce nitrogen losses.

FUTURE PLANS: In 1995, the studies on cotton will be continued without the use of benzoic acid tracers that affect the growth development of the plant. Additional irrigation methods also need to be investigated. The rates of movement of chemical tracers and labelled nitrogen will be used to assess the impact of preferential flow. The data set should be suitable for evaluating current soil models that predict the quality of water moving below the root zone. If no suitable models exist, a model development and verification effort can be initiated.

COOPERATORS: J. E. Watson, The University of Arizona Maricopa Agricultural Center, Maricopa, Arizona; T. L. Thompson, University of Arizona Department of Soil and Water Science, Tucson, Arizona.

Table 1. Yield of wheat from the 1993-1994 irrigation and fertilizer management study.

Nitrogen Application Method	80 % ET	100 % ET	120 % ET	Average
	kg ha^{-1}			
Standard	3045	3084	3159	3,096
BMP	2750	3206	3162	3,039
Average	2,898	3,145	3,161	3,068

Table 2. Lint yield of cotton from the 1994 irrigation and fertilizer management study.

Nitrogen Application Method	80% ET	100% ET	120 % ET	Average
	kg ha^{-1}			
Standard	343	353	523	406
BMP	280	297	393	323
Average	312	325	458	365

Table 3. Seed yield of cotton from the 1994 irrigation and fertilizer management study.

Nitrogen Application Method	80% ET	100% ET	120 % ET	Average
	kg ha^{-1}			
Standard	667	647	937	750
BMP	577	627	903	702
Average	622	637	920	726

Table 4. Recovery of fertilizer nitrogen in wheat straw, grain and soil from the 1991-1992 growing season.

	STD 80	STD 100	STD 120	BMP 80	BMP 100	BMP 120
	kg ha^{-1}					
Straw	6.2	5.8	6.9	5.2	4.1	4.5
Grain	24.3	23.6	29.0	21.4	19.2	19.3
Soil	68.8	77.2	71.7	69.9	78.8	65.0
Total	99.3	106.6	107.6	96.5	102.1	88.8

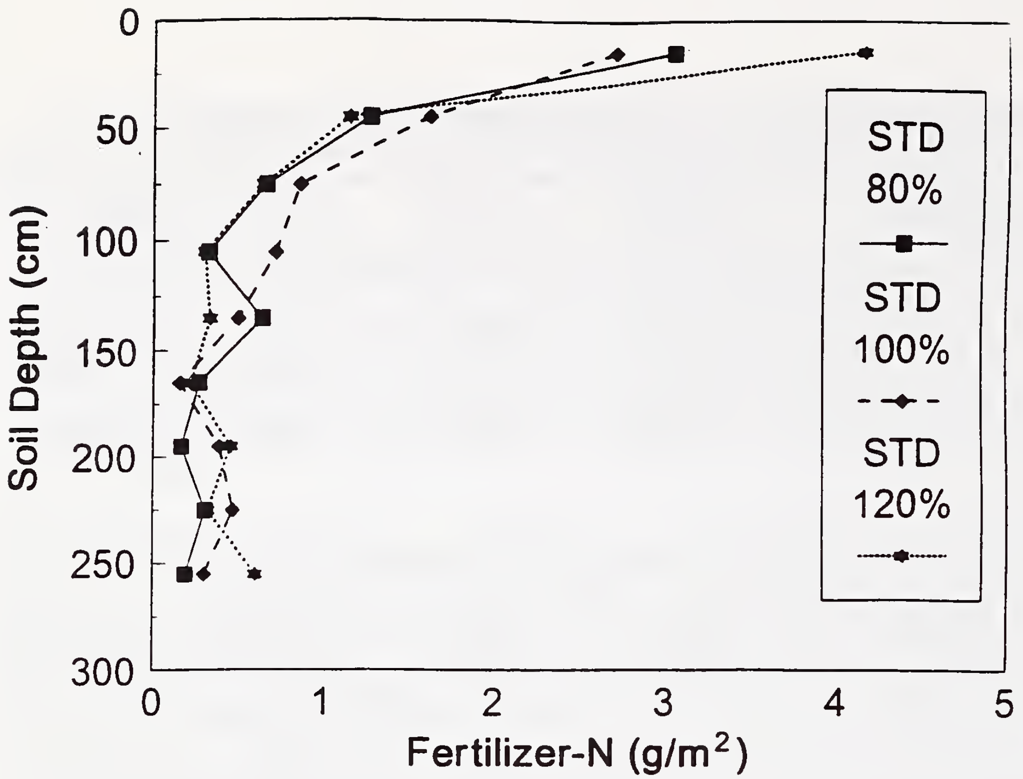

Figure 1. Fertilizer-N distribution in soil from plots receiving the standard (STD) fertilizer treatment.

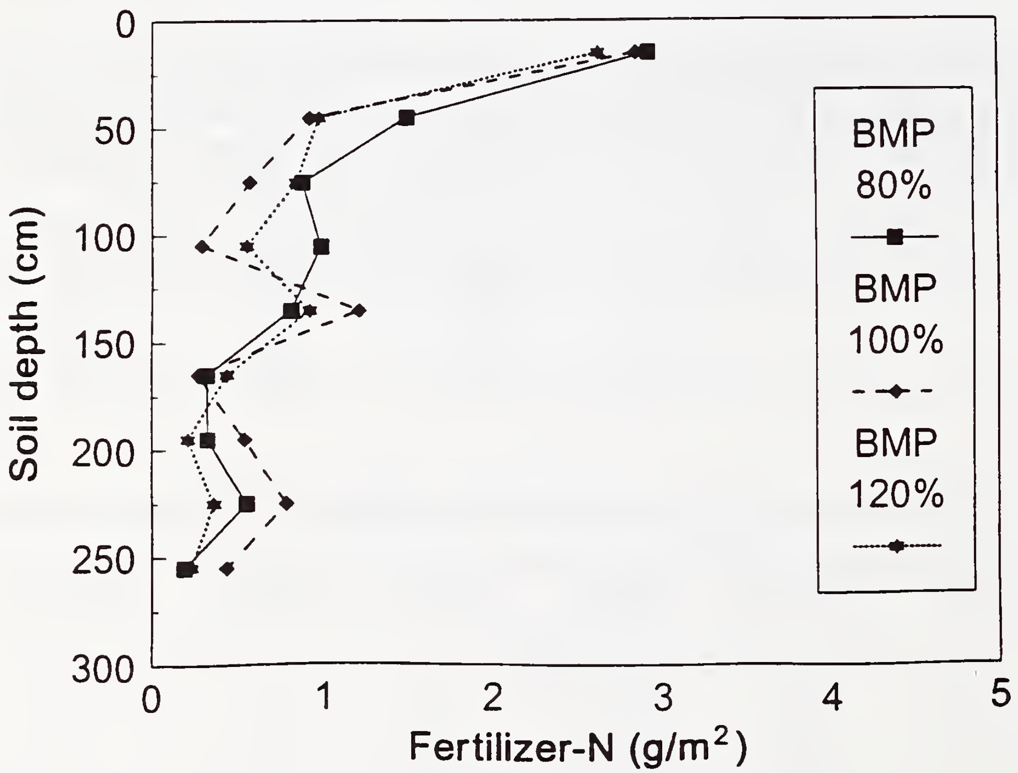

Figure 2. Fertilizer-N distribution in soil from plots receiving the best management practices (BMP) fertilizer treatment.

EVALUATION OF RAPE AND CRAMBE AS POTENTIAL WINTER CROPS TO REDUCE NITRATE ACCUMULATION IN THE SOIL

F.J. Adamsen, Soil Scientist; W.L. Alexander, Agronomist; and R.C. Rice, Agricultural Engineer

PROBLEM: Formation of nitrate during fallow periods in irrigated cotton rotation systems can lead to leaching of nitrate to groundwater when preplant irrigations are applied in order to make the soil suitable for tillage operations. One solution to this problem is growing a winter crop that utilizes residual nitrogen and nitrate mineralized during the winter. Generally, any crop grown in the winter under irrigated conditions must have an economic return in order to gain producer acceptance, and a crop must be found that can be planted after cotton is harvested in the fall and can be harvested before cotton is planted in the spring. Two crops that may meet these restrictions are rape and crambe. Industrial rape and crambe both contain erucic acid, which has industrial potential, and Canola types of rape are valuable as sources of unsaturated cooking oil. Both of these crops are short, cool season crops that may meet the short growing season requirement and have a significant nitrogen requirement that would take advantage of residual nitrogen in the soil.

APPROACH: Research is being conducted through a series of field experiments to evaluate yield potential and maturity dates of rape and crambe. One variety of spring-type industrial rape, eight varieties of spring Canola-type rape, and one variety of crambe were planted in the 1993-1994 growing season in 2 X 12.2-m plots on three planting dates from late October to early December. Row spacing was 0.25 m. For the 1994-1995 growing season, one variety of crambe, one variety of mustard, one variety of spring type industrial rape, and seven varieties of spring Canola-type of rape were planted with three planting dates from late October through mid-December.

FINDINGS: In the 1993-1994 crop year, rodents ate all of the Canola-type in the first planting date but did not damage the Crambe and R-500, which is an industrial rape. Both of the untouched crops contained high levels of glucosinolates, which make them unpalatable. Before the second planting date, a rodent control program was instituted, which controlled the population of the pests, and the second and third planting dates were not affected. A chemical residual present in the field affected the first two reps of the experiment, leaving only one usable rep.

Harvest dates varied from March 29 to April 26 (table 1). The earliest variety was R-500, and this also was the best yield obtained in the experiment. Crambe yields increased as the planting date was later. This may reflect a response to temperature during seed set. All of the Canola types were almost two weeks later than the R-500, and the yields were much lower. The yield potential of Canola types is usually much higher than for R-500 and other campestera types of rape. The differences may reflect differences in pest problems that were not recognized or may result from different responses to temperature, which give R-500 a yield advantage.

INTERPRETATION: R-500 matured early enough to follow cotton in a double cropping system. The plant responded to planting date more than was expected, which may be an advantage because it provides a fairly wide window for both planting and harvesting, which would fit the logistics of most farm operations. The Canola types used in this study were not early enough for most farmers to use in a double crop system. However, the earliest planting date was lost to pests and chemical damage so data are available for early planting that may overcome part of the lateness of the Canola type. The same was true for Crambe as for the Canola types. There may be early maturing varieties available for this crop that may still make it a viable alternative.

FUTURE PLANS: In 1995, evaluation of rape and crambe will be continued, and a variety of mustard will be added to the study. Additional early maturing varieties of rape from the Colorado breeding program will be added to the program, and earlier maturing varieties of Crambe will be sought. Irrigation and other agronomic studies will be conducted to make the yields of winter crops economical. The results of the planting date by variety trial will used to develop a rotation system with cotton that will provide year-round cover on the soil and should improve year-round nitrogen management.

COOPERATORS: Paul Raymer, Coastal Plain Experiment Station, Tifton, Georgia; Larry Sernek, Agrigenetics, Madison, Wisconsin; Jennifer Mitchell Fetch, University of North Dakota, Fargo.

Table 1. Rape and Crambe yields in the 1993-1994 crop year at Maricopa Agricultural Center. All data are based on replication.

Variety	Planting Date	Harvest Date	Yield kg ha^{-1}	Planting Date	Harvest Date	Yield kg ha^{-1}	Planting Date	Harvest Date	Yield kg ha^{-1}
R-500	26 Oct	29 Mar	2822	22 Nov	6 Apr	1030	3 Dec	13 Apr	1039
Crambe	26 Oct	13 Apr	698	22 Nov	20 Apr	1238	3 Dec	26 Apr	2053
Garrison	26 Oct	--	--	22 Nov	20 Apr	512	3 Dec	26 Apr	452
Cyclone	26 Oct	--	--	22 Nov	20 Apr	590	3 Dec	26 Apr	304
Excel	26 Oct	--	--	22 Nov	20 Apr	397	3 Dec	26 Apr	195
Bingo	26 Oct	--	--	22 Nov	20 Apr	802	3 Dec	26 Apr	153
Printol	26 Oct	--	--	22 Nov	20 Apr	113	3 Dec	26 Apr	353
Iris	26 Oct	--	--	22 Nov	20 Apr	546	3 Dec	26 Apr	371
188-20-B	26 Oct	--	--	22 Nov	20 Apr	304	3 Dec	26 Apr	216
188-25-B	26 Oct	--	--	22 Nov	20 Apr	337	3 Dec	26 Apr	262

ASSESSMENT OF NITRATE LEACHING UNDER COMMERCIAL FIELDS

F. J. Adamsen, Soil Scientist; and R. C. Rice, Agricultural Engineer

PROBLEM: Application of excess nitrogen to crops such as cotton and subsequent application of excess irrigation water can result in movement of nitrate to groundwater. When nitrate is found in groundwater, agriculture is usually assumed to be the source of the contamination. A number of surveys of Midwest fields indicate that farm practices are responsible for at least part of the nitrate that finds it way into groundwater. Under irrigated conditions, nitrate leaching is a function of irrigation efficiency and spatial variability as well as fertilizer management, which makes assessment of the problem more complex.

APPROACH: Research is being conducted by taking soil samples from commercial fields after a crop has been harvested. Three transects are taken across each field with five samples taken in each transect. Spacing of samples along the transect are based on the length of the run. The first sample was taken 10% of the of the run length from the top of the field. The next four samples were taken 20% of the run length apart. A 2-m-by-2-m area was amended with KBr before the start of the growing season so that the depth of penetration of that season's irrigation water could be determined. The positions in the transect are numbered from one to five, starting at the upper end of the field. Samples are taken to a depth of 270 cm and analyzed for ammonium, nitrate, bromide, chloride, and texture. Water samples are taken from each irrigation, and the concentrations of chloride, nitrate, and ammonium determined. Chloride values in the soil will be used to provide a crude estimate of actual evapotranspiration. In 1994, samples were taken from four fields on two farms. Two of the fields were planted to cotton and the other two to wheat. Three of the fields have no runoff and the fourth is sloping with runoff. In the fourth field, flumes were installed to allow measurement of water entering and leaving the field. Automated data collection systems were operated during each irrigation during the 1994 growing season for cotton.

FINDINGS: Most of the effort was expended on the field with runoff. The amount of runoff varied throughout the season. Early in the season, runoff amounted to 25% of the amount applied, but later in the season it dropped below 20%. Input and runoff hydrograms were plotted for each irrigation (fig. 1), and the amount of water applied was calculated by the difference of the integration of the two curves. Irrigations usually took several days, and during the peak water use, irrigation was conducted almost continuously.

Samples were take at the end of the growing season from the two fields that were in cotton. These samples are currently being analyzed.

INTERPRETATION: Based on the observations made during the growing season, uniformity of application, especially in sloped fields is poor. This is a result of both soil variation and application differences. Because there were at least two irrigators working during each irrigation, a night irrigator and a day irrigator, differences in application occurred. Length of run and soil variability both have affected movement of nitrate in previous years.

FUTURE PLANS: In 1995, the study will be expanded to include additional producers in the Yuma area. Selection of additional sites will be based on the crop rotations, soil type, and irrigation method.

COOPERATORS: Buddy Ekholt, Pinal County Irrigation Management Program, Casa Grande, Arizona; T. L. Thompson, University of Arizona, Dept. of Soil and Water Science, Tucson, Arizona.

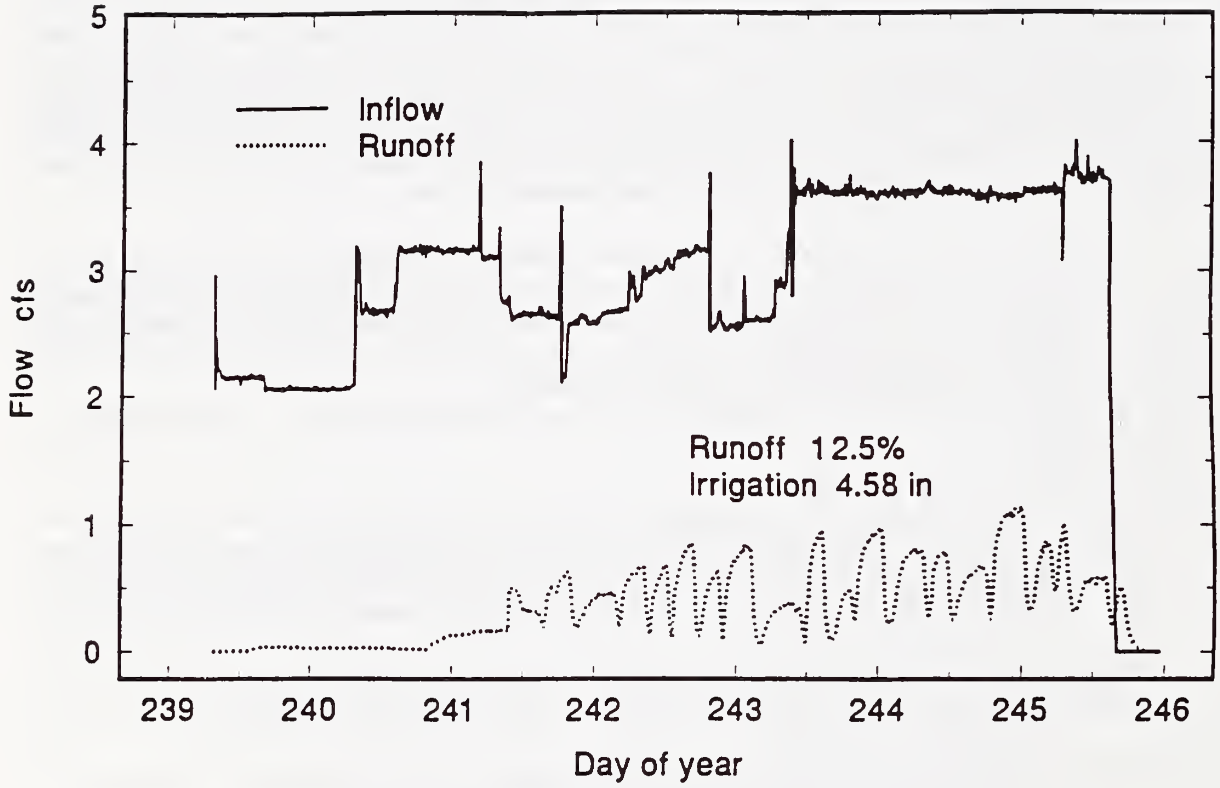

Figure 1. Example of water inflow and runoff for field 1-OL for the irrigation starting August 27, 1994, and ending September 4, 1994.

SIMULATION OF CHEMICAL TRANSPORT IN SOILS FROM SURFACE IRRIGATION

T.S. Strelkoff, Research Hydraulic Engineer; F.J. Adamsen, Soil Scientist;
and A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Irrigation management influences the quality of both surface and groundwater supplies. Chemigation introduces agricultural chemicals into the irrigation water. Initially clean irrigation water picks up agricultural chemicals and naturally occurring minerals, some toxic, from the surface of fields and from contact by percolation through the porous soil medium. Nitrogen, chlorinated organic compounds, and heavy metals, for example, brought to farm fields in the course of agricultural operations, and naturally occurring chemicals, like selenium, can be transported to surface or subsurface water supplies by the movement of irrigation water, to the detriment both of human consumers of the water resource and wildlife dependent on these bodies of water.

The transport, transformation, and ultimate fate of chemical components of the irrigation water depend on the quantities of water remaining in the root zone after the irrigation, the quantities running off the end of the fields into drainage ditches and canals, and the quantities that continue to percolate through the soil, entering eventually either a groundwater aquifer or a river fed from groundwater seepage. The chemical and physical reactions between the water, the soil medium, and the particular chemicals involved significantly influence the transformation and ultimate fate of the chemical constituents. Preferential flow, fingering of the water front advancing downward through the soil medium, occurs both as the result of nonhomogeneous soil, with worm and root channels, and layering of soils with a layer of low permeability overlying one of great permeability. This results in more rapid transport of waterborne constituents to the groundwater table than with reasonably homogeneous soils.

In the porous subsurface medium, many existing models view variation in only one dimension, the vertical, assuming no movement parallel to the stream flow. However, *interflow* is known to occur, especially on steep slopes and, in fact, provides a means of transport of groundwater, along with its chemical constituents, into surface streams.

The goal of this research effort is a predictive tool, a computer model, capable of simulating the response of a given agricultural field and its geologic site to one or another irrigation-management practice. Computer simulations would allow swift comparisons among various trial management modes in a program to seek optimum solutions. This would make possible recommendations on the basis of environmental considerations as well as upon water conservation and crop yield.

APPROACH: Two different problems comprise the subject of investigation: (1) transport of a contaminant by irrigation water from a contaminated soil-surface layer to stream flow and to the groundwater via deep percolation, and (2) the distribution of a chemical introduced nonuniformly with the irrigation inflow, e.g., a pulse of chemical introduced at some time after the start of irrigation. Both problems are to be treated by a plane two-dimensional (longitudinal and vertical) mathematical simulation, coupling a solution of the turbulent Navier-Stokes equations augmented with a two-equation turbulence model in the surface stream to a solution of the equations for unsaturated flow in a porous medium in the underlying soil. The two regions share a common vertical velocity field at the interface.

Mass transport is modeled in the entire system through dispersivities calculated from the flow equations. Sorption and desorption are incorporated in terms of both equilibrium and nonequilibrium kinetics of semi-empirical determination. The same is true for volatilization, degradation, and leaching processes, incorporated as sink terms in the mass transport model.

A physical model with a graded sand bed is to be used for verification of the mathematical model.

FINDINGS: A reasonably robust algorithm for the surface stream is now based on a combination of deforming finite elements and markers. The markers, which track the movement of water particles, are allowed to move freely with the fluid velocity and so may penetrate the initial free surface during any given time step. The envelope of their new position is constructed at the start of each new time step and the deforming grid fitted thereto, with the finest cells associated with the front, where gradients are the largest (see fig. 1). There is no longer need for a fictitious, traction-free outflow boundary at the front, since the whole free surface is treated as a boundary where normal stresses vanish. The subsurface model's automatic grid generation has also been improved, so most instabilities traceable to the subsurface wetting front have been eliminated. An erosion component has been added to the surface transport model. Based on shear values from the flow model, new sediment is introduced through

the source term for suspended solids. A similar empirical equation is used as a sink for the settling of sediment, but at present it has not proved possible to calibrate that component. It may be that for the types of flows examined, no deposition is possible, but experiments are continuing with data from the literature.

In the chemical fate and transport model, a stiffness-matrix splitting routine has been developed for separating adsorbed and dissolved species. Equilibrium velocities are assumed for adsorption, with a partition coefficient required for each species. Immobile or adsorbed species are not part of the advection or dispersion process but can enter the reaction process of mobile species. Three types of bacteria have been incorporated in the model as entirely immobile species. Modeling for oxygen, organic matter supplied by the root zone, and the bacteria has produced reasonable results for the transport of oxygen and organics. Sample chemical reactions depending on the presence of oxygen and soil bacteria have also been included. Although realistic values for reaction velocities are lacking, qualitative results have been produced indicating sorption and dissolution effects and, in addition, natural degradation due to soil bacteria.

The physical model, a flume 3 *m* long, 0.3 *m* wide, and 0.38 *m* deep, with changeable slope has been constructed of Plexiglas, with a steel framework to provide strength (fig. 2). Soil boards, consisting of plates with a thin layer of the selected soil cemented to the surface, are attached to the floor fore and aft of the test section to avoid disturbing the stable velocity profile. A constant-head reservoir introduces aqueous solutions containing the chemical of interest through a U-shaped tube from below the level of the soil surface to reduce turbulence.

INTERPRETATION: The simulation model is too new to have yielded significant results to date. It shows promise, however, for simulating the subject phenomena to a useful degree. With increased reliability and verification, it should serve both as a research tool in evaluating one or another irrigation management practice and as a theoretical base for more approximate, more practical simulations.

FUTURE PLANS: The mathematical model will be exercised over a range of practical conditions to establish and strengthen its reliability. Specific chemical constituents to be incorporated into the model will be selected, along with currently available figures on reaction kinetics, to substitute for the present hypothetical assumptions. The physical flume will be completed and operated to test the various model assumptions, establish appropriate values for numerical solution parameters, and verify its performance.

Syringe needles attached to Luer-lock fittings will be placed along one side of the flume for sample collection. The needles will be positioned so that three extend into the soil profile and one extends into the surface water layer. The system is designed to allow collection of very small sample volumes (a few microliters), which will minimize any disruption of flow caused by sample collection. The samples will be assayed for the chemical of concern by use of an automated HPLC system.

COOPERATORS: N.D. Katopodes, University of Michigan; M.L. Brusseau, P.M. Waller, The University of Arizona.

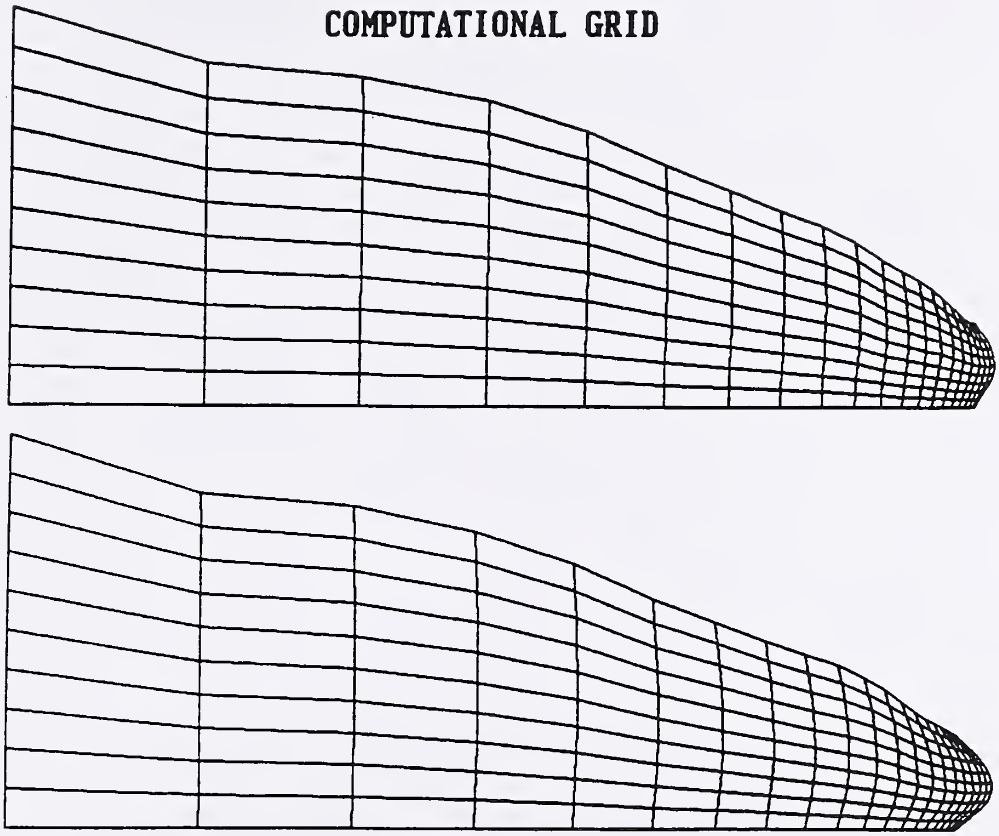

Figure 1. Evolution of the computational grid in the surface.

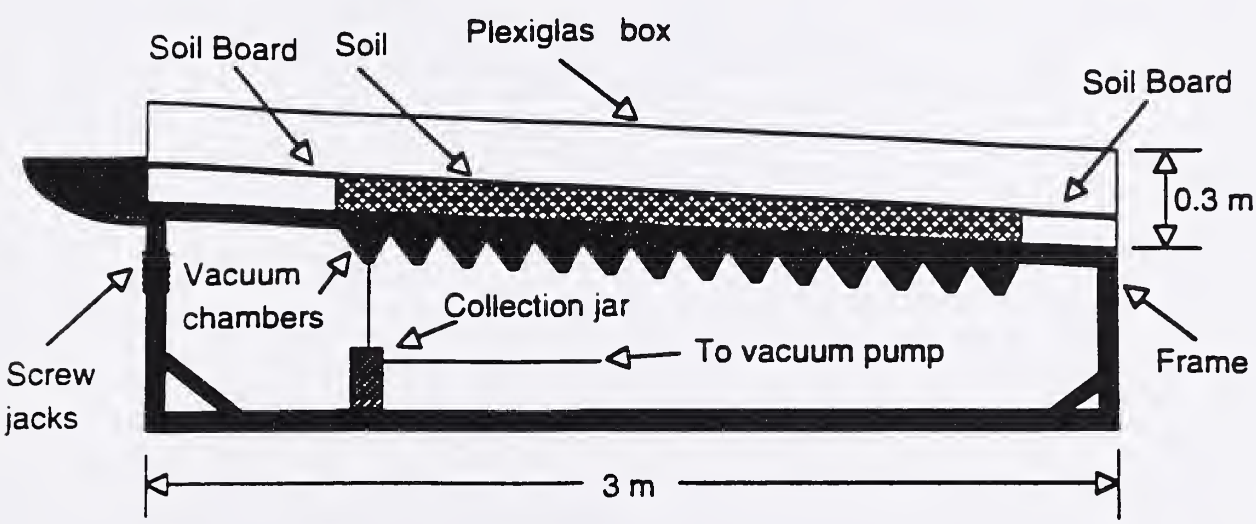

Figure 2. Layout of laboratory flume.

PLANT GROWTH AND WATER USE AS AFFECTED BY ELEVATED CO_2 AND OTHER ENVIRONMENTAL VARIABLES

PROGRESS AND PLANS FOR THE FREE-AIR CO_2 ENRICHMENT (FACE) PROJECT

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PROBLEM: The CO_2 concentration of the atmosphere is increasing and expected to double sometime during the next century. Climate modelers have predicted that the increase in CO_2 will cause the Earth to warm and precipitation patterns to be altered. This project seeks to determine the effects of such an increase in CO_2 concentration and any concomitant climate change on the future productivity, physiology, and water use of crops.

APPROACH: Numerous CO_2 enrichment studies in greenhouses and growth chambers have suggested that growth of most plants should increase about 30% on the average with a projected doubling of the atmospheric CO_2 concentration. However, the applicability of such work to the growth of plants outdoors under less ideal conditions has been seriously questioned. The only approach whose realism is unquestioned and which can produce an environment as representative of future fields as possible today is the free-air CO_2 enrichment (FACE) approach.

The FACE approach has been criticized because the prodigious quantities of CO_2 required make it expensive. A FACE experiment is expensive, but because of the relatively large area of the FACE plots, there is a huge economy of scale, so that per unit of treated plant material, FACE costs 1/4 or even less than the cost of other approaches. Thus, there is an economic incentive to have many scientists cooperate on large, comprehensive FACE experiments.

About 20 scientists from ARS, Brookhaven National Laboratory, and several universities have cooperated on a FACE project from 1989 to 1991 at the University of Arizona's Maricopa Agricultural Center (MAC). These experiments have yielded a wealth of information about the growth and physiological responses of cotton to elevated CO_2, at ample and limiting supplies of water. A 17-chapter book, *FACE: Free-Air CO_2 Enrichment for Plant Research in the Field*, edited by G. R. Hendrey, was published in 1993 covering the FACE work up through 1989. Another 21 papers covering the 1990 and 1991 cotton experiments have recently been published in a special issue of *Agricultural and Forest Meteorology*, edited by W.A. Dugas and P.J. Pinter, Jr. Data sets in IBSNAT format suitable for validation of plant growth models have been prepared.

From December 1992 through May 1993 and from December 1993 through May 1994 two more FACE experiments were conducted, this time on wheat at ample and limiting levels of water supply. Fifty scientists from 25 different research organizations in eight countries have participated, measuring leaf area, plant height, above-ground biomass plus roots that remained when the plants were pulled, apical and morphological development, canopy temperature, reflectance, chlorophyll, light use efficiency, energy balance, evapotranspiration, soil and plant elemental analyses, soil water content, sap flow, root biomass from soil cores, photosynthesis, respiration, stomatal conductance, leaf water potential, carbohydrates, photosynthetic proteins, antioxidants, stomatal density and anatomy, digestibility, decomposition, grain quality, soil CO_2 fluxes, and changes in soil C storage from soil and plant C isotopes. All of the data will be assembled in a standard format for validation of wheat growth models. Seven collaborating wheat growth modelers plan to utilize the data.

FINDINGS: It is beyond the scope of this report to review the results presented in the numerous above-mentioned manuscripts. Briefly however, averaged over three years, cotton yields were increased about 40% with CO_2 concentrations elevated to 550 ppm, and there was no significant increase in water use.

Analyses of the wheat data from 1992-4 are not complete. However, the growth, morphological development, soil water balance, and energy balance aspects are reported in this volume[1] by Pinter et al., Wall et al., Hunsaker et al., and Kimball et al. Briefly, wheat responded much differently than cotton to elevated CO_2. Early in the season in January and February when temperatures were cool, there was little response to CO_2 (concentrations of 550 μmol/mol and ambient). Then as temperatures warmed into spring, the FACE plants grew about 20% more than

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[1]See "Effects of Free-Air CO_2 Enrichment on Spring Wheat Growth and Yield" by Pinter et al., "Diurnal Trends in Total Water Potential of Leaves of Spring Wheat Grown in a Free-Air CO_2-Enriched (FACE) Atmosphere and Under Variable Soil Moisture Regimes" by Wall et al., "Wheat Evapotranspiration under CO_2 Enrichment and Variable Soil Moisture" by Hunsaker et al., and "Effects of Free-Air CO_2 Enrichment (FACE) on the Energy Balance and Evapotranspiration of Wheat" by Kimball et al.

the CONTROL plants at ambient CO_2. The number of tillers per plant was increased from about 4 to 5. Then in May a surprising thing happened. The FACE plants matured and senesced earlier by 7-10 days than the CONTROLs, such that the extra growing time allowed the CONTROL plants to narrow the final difference to about 10% in the well-watered plots, while the difference remained at about 20% in the water-stressed plots. The FACE plants averaged 0.6°C warmer than the CONTROLs, day and night, all season long, in the well-watered plots, and we speculate that this temperature rise caused the earlier maturity. The energy balance and the sap flow data showed decreases in evapotranspiration of about 10% in the well-watered plots. Although the soil water balance measurements showed a similar trend, the difference was not statistically significant.

INTERPRETATION: The increasing atmospheric CO_2 concentration should be beneficial to future cotton production and probably other indeterminate crops growing in warm climates, provided water supplies do not change significantly. However, cool-season determinate crops such as wheat probably will benefit also, but not as much. Irrigation requirements may be somewhat reduced for future wheat production, provided climate changes are minimal.

FUTURE PLANS: FACE wheat experiments at ample and limiting supplies of soil nitrogen will be conducted in 1995-6 and 1996-7, funded by the Department of Energy through a grant to the University of Arizona. U.S. Water Conservation Laboratory personnel will be major collaborators on the project and will provide management support. To prepare for these upcoming experiments, the FACE field at Maricopa has been planted to a crop of oats which will be green chopped and removed from the field in order to withdraw as much nitrogen as possible from the soil. During the summer of 1995, new drip irrigation tubing will be installed, and the plots will be moved about 25 m south of the their present locations.

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EFFECTS OF FREE-AIR CO_2 ENRICHMENT ON SPRING WHEAT GROWTH AND YIELD

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R.L. LaMorte, Civil Engineer; G.W. Wall, Plant Physiologist;
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PROBLEM: Net photosynthetic rates for many food and fiber crops are limited by present concentrations of atmospheric carbon dioxide (CO_2). As a result, anticipated changes in global climate and atmospheric CO_2 concentrations have very important consequences for world agriculture. Mounting evidence shows positive effects of CO_2 on plant growth when nutrients are not limiting, but few studies have been conducted under natural field conditions without the use of chambers. Beginning in 1992 and continuing for the past 2 seasons, a Free Air Carbon dioxide Enrichment (FACE) facility was used to study the effects of supra-ambient concentrations of CO_2 on growth and yield of spring wheat in a realistic, open field, production environment. This report discusses preliminary results from the second season and presents yield comparisons for both years.

APPROACH: Observations of wheat development, biomass, and final grain yield were made at the University of Arizona's Maricopa Agricultural Center (MAC), south of Phoenix, Arizona. Spring wheat (*Triticum aestivum* L. cv Yecora Rojo) was sown December 7-8, 1993, in east-west rows spaced 0.25 m apart. Cultural practices (cultivation, insect control, soil nutrient levels, etc.) were typical of those recommended by state Cooperative and University research staff. Plants were exposed to enriched (FACE, ~550 μmol mol^{-1}) and ambient (CONTROL, ~370 μmol mol^{-1}) CO_2 levels; treatments were replicated four times. Enrichment began on December 28, 1993, (50% emergence) and continued 24 hours a day until FACE plants were mature (May 16, 1994). CO_2 treatment plots were split to test the effect of different irrigation amounts on wheat response to CO_2. Irrigation of the WET treatment was based on consumptive use requirements determined from estimates of daily potential evapotranspiration multiplied by an appropriate crop coefficient for wheat. Plants in the DRY irrigation treatment received 50% of amounts delivered to the WET. Irrigation water was delivered to the plants using micro-irrigation (drip) tubing that was spaced 0.51 m apart (parallel to plant rows) and buried about 0.22 m deep. Irrigation amounts from emergence to harvest averaged 600 mm for the WET treatments, while DRY treatments received 257 mm. Rainfall during the same period was 61 mm. Plants received 214 kg N ha^{-1} and 24 kg P ha^{-1}.

Approximately 24 wheat plants were sampled from all replicates of each treatment combination at 7-day intervals during the season. Plant phenology of the main stem was determined according to both the Zadoks and Haun scales of development. Green leaf and green stem area was measured on a subsample of 12 median-sized plants using an optical planimeter. Numbers of stems and heads were counted. Crown, stem, green and nongreen leaf, and head components of subsample and remaining (~12) plants were separated. Component biomass was measured after oven-drying at 65-70 °C. Leaf area index was computed from subsample specific leaf weight and green leaf biomass of all plants. Beginning on April 5 (about 1 week after anthesis), developing grains were separated from chaff by a combination of hand and machine threshing of heads that were pooled by subplot. Grain was oven-dried for a total of 14 days at 65-70 °C. Final grain yield was determined by field harvest of a ~20 m^{-2} area of each subplot on June 1, 1994.

Data were analyzed using the ANOVA procedures of the Statistical Analysis System (SAS Institute, Inc.). A split-plot model was used which included CO_2 (main plot), replication, irrigation (as a strip, split plot), and appropriate interaction terms. The CO_2 treatment effect was tested using the mean square of the CO_2 by replicate interaction as the error term; irrigation effects were tested using the residual mean square error term.

FINDINGS: Seasonal trajectories of biomass revealed relatively slow growth rates during winter when temperatures were cool (fig. 1). Data are shown for six plant components: 1) crown, including the portion of the stem which is below the ground surface; 2) stem, above-ground culm including the attached leaf sheaths; 3) green leaf blade tissue; 4) B Leaf, non-green leaf tissue; 5) chaff, non-grain head tissue; and 6) grain. As temperatures warmed in March, biomass began to increase exponentially and the effects of elevated CO_2 and deficit irrigation became more noticeable. As we first observed in the 1992-93 season, developmental rates were accelerated by elevated levels of CO_2 (table 1). Plants exposed to FACE WET reached anthesis and maturity several days earlier than CONTROLS. The relative effects of CO_2 on plant biomass and green leaf area index are shown by a CO_2 enhancement factor graphed as a function of sampling date in 1994 (fig. 2). Patterns were qualitatively similar to those observed during the 1992-93 experiment. The CO_2 factor for biomass increased gradually at the beginning

of the season, reaching values around 0.35 in the DRY treatment and varying around 0.20 to 0.25 in the WET treatment. After anthesis in late March, leaf senescence progressed more rapidly in the CO_2-enriched canopies, and biomass in FACE treatments declined relative to the CONTROLS. These data support a hypothesis that the determinate growth patterns of wheat render it sink-limited when exposed to supra-ambient CO_2 levels.

On a per plant basis, components contributing to final yield for each of the treatment combinations during the 1993-94 season (fig. 3) were lower than those observed the previous season. This was attributed to higher initial seeding rates and final plant densities (152 per m^2 during 1993-94 vs. 109 per m^2 during the first year). Compared with their CONTROL counterparts, FACE treatments produced more early season stems per plant, but also sustained a higher tiller abortion rate during mid-season. Thus, at the end of the season, we observed essentially no difference between CO_2 treatments in number of stems per plant. Early differences in rates of head appearance emphasized the accelerated phenological development in CO_2 treatments. After anthesis however, differences caused by elevated CO_2 in the number of heads per plant also largely disappeared. Water stress reduced the number of heads by about 25%. CONTROL WET appeared to produce slightly more kernels per head than any of the other treatments. Kernel size was typically very different while grains were filling. End-of-season kernel weight was greatest in FACE DRY and, as in the previous year's experiment, least in CONTROL WET.

Yields obtained under the well-watered conditions of our study were very high during both years (table 2). In fact, plants in the CONTROL WET treatment during the 1992-93 season produced 40% more grain than the county averages for spring wheat and 10% more than the potential yields listed by *CIMMYT* for the same cultivar. The effects of our experimental treatments on yield were also very consistent over both years. Grain yields in the DRY treatments were reduced an average of 28% compared with the well-watered treatments. In the WET irrigation treatments, end-of-season yields in FACE were increased by an average 10% compared with CONTROLS; yield enhancement in the DRY treatments averaged 23%. Analysis of variance revealed that the differences between CO_2 treatment means were statistically significant at $p=0.037$ in 1992-93 and $p=0.062$ in 1993-94. Differences between irrigation treatment means were significant at $p<0.01$ during both seasons.

INTERPRETATION: Our results revealed that the biomass and final yield responses of Yecora Rojo wheat to elevated CO_2 in FACE were less than those reported in the literature for controlled environment studies. However, the effect of CO_2 that we observed was very consistent over both years. The high yields we obtained in the WET irrigation treatments suggest near-optimum conditions for growth, and it is possible that upper limits for yield in this cultivar are sink-limited and genetically constrained. We did find that the effect of CO_2 on yield was enhanced when suboptimal growing conditions reduced yields below maximum levels.

The CO_2 effects on wheat were also much lower than responses observed for upland cotton in the FACE facility. Several hypotheses have been proposed for these differences. Wheat is a cool season, annual plant. It has determinate growth and yield characteristics resulting in early senescence of photosynthesizing canopy elements and accelerated maturation of grain. This causes a late-season sink limitation which may prevent full utilization of additional CO_2 as temperatures rise during the spring. In contrast, the warm season, perennial, nondeterminate fruiting patterns of cotton enable it to exploit more fully the advantage of elevated CO_2 levels.

FUTURE PLANS: Analysis of wheat growth data is continuing. Important questions remain concerning wheat response to CO_2 under conditions of limited nitrogen availability. As a result, similar FACE experiments using wheat exposed to two levels of soil nitrogen are planned for the 1995-96 and 1996-97 growing seasons.

COOPERATORS: A very large number of research organizations took an active role in supporting our 1992-93 FACE experiment. See "Progress and Plans for the Free-Air CO_2 (FACE) Enrichment Project" (Kimball *et al.*, in this publication) for a complete listing of cooperators. The authors wish to acknowledge the technical assistance of C. O'Brien, T. Brooks, K. West, and O. Cole in processing weekly plant samples.

Table 1. Phenological development of spring wheat, *T. aestivum* L. cv Yecora Rojo, in the 1993-94 experiment. Data represent starting day-of-year for growth stages according to the Zadoks scale of plant development.

ZADOKS GROWTH STAGE		EXPERIMENTAL TREATMENTS			
Description	Code	CD	CW	FD	FW
Seedling Growth	10-19	362	362	362	362
Tillering	20-29	23.2	23.6	23.2	22.9
Stem Elongation	30-39	55.2	55.7	54.7	52.4
Booting	40-49	76.5	78.5	74.6	75.6
Inflorescence Emergence	50-59	83.2	87.3	79.7	82.7
Anthesis	60-69	90.7	93.5	89.1	90.0
Milk Development	70-97	98.3	100.9	94.5	95.6
Dough Development	80-89	112.8	116.6	111.9	112.2
Ripening	90-92	134.3	142.3	131.4	137.6
Maturity	92	137.3	144.9	136.1	142.8

Table 2. Final grain yields (dry weight) of spring wheat, *T. aestivum* L. cv Yecora Rojo, from 2 years of FACE experiments. Data are means ($\pm$ 1 standard error) of 4 replicated subplots of each treatment combination.

		CONTROL (Mg ha^{-1} $\pm$ se)	FACE (Mg ha^{-1} $\pm$ se)	Ratio (FACE:CONTROL)
1992-93	DRY	5.96 $\pm$ 0.05	7.20 $\pm$ 0.30	1.21
	WET	8.37 $\pm$ 0.21	9.04 $\pm$ 0.28	1.08
Ratio (DRY:WET)		0.71	0.80	---
1993-94	DRY	4.74 $\pm$ 0.36	5.92 $\pm$ 0.35	1.25
	WET	7.44 $\pm$ 0.44	8.31 $\pm$ 0.14	1.12
Ratio (DRY:WET)		0.64	0.71	---

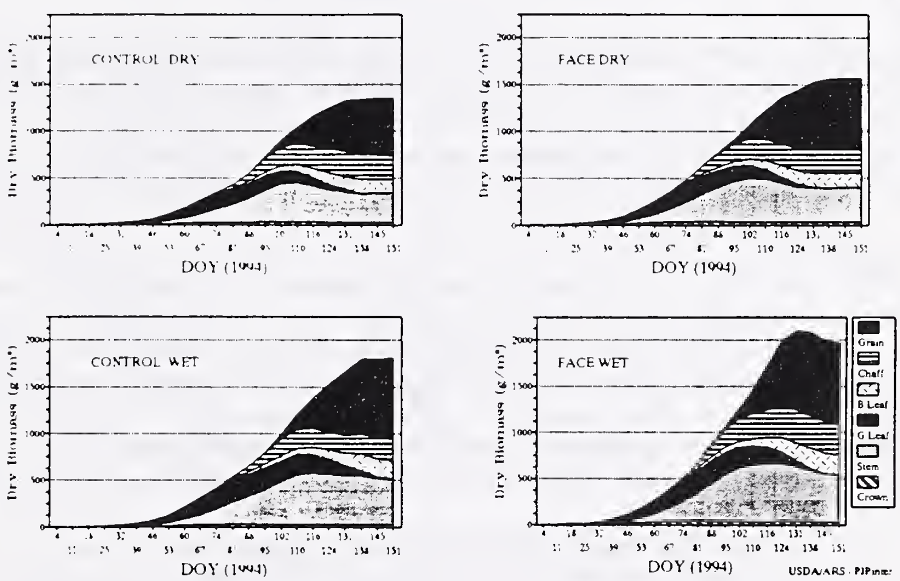

Figure 1. Seasonal trajectories of dry biomass accumulation in spring wheat in the 1993-94 FACE experiment. These data were smoothed by a 3-term running average. DOY refers to day-of-year that samples were taken.

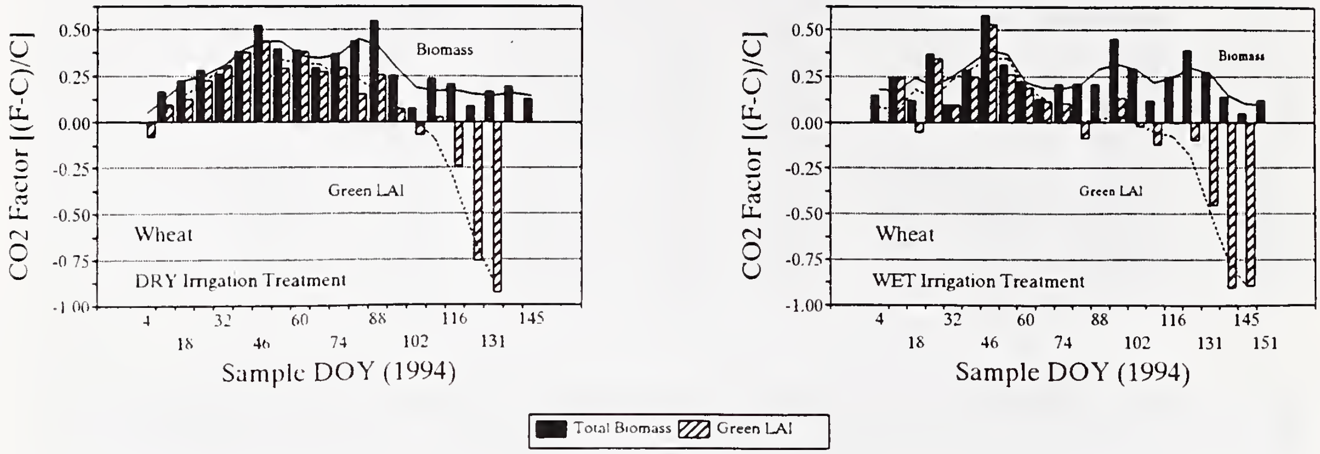

Figure 2. CO_2 enhancement factor showing relative CO_2 effects on plant biomass and green leaf area index as a function of day-of-year (DOY). The factor is calculated as the FACE response minus CONTROL response divided by the CONTROL response. In this figure the actual data are shown by bars; lines show a 3-term running average.

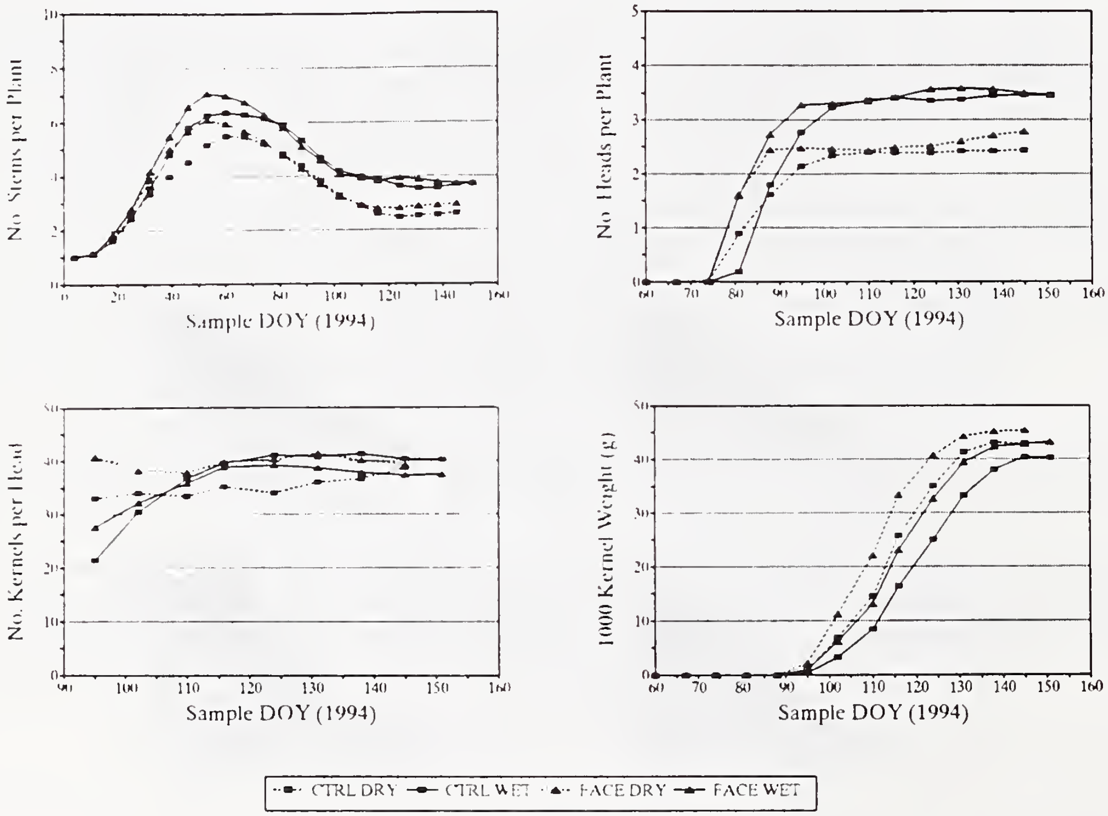

Figure 3. Components contributing to final yield for each of the treatment combinations. Plant density at time of harvest averaged 152 plants m^{-2}. Kernel mass is presented on a dry weight basis.

EFFECTS OF FREE-AIR CO_2 ENRICHMENT (FACE) ON THE ENERGY BALANCE AND EVAPOTRANSPIRATION OF WHEAT

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PROBLEM: The CO_2 concentration of the atmosphere is increasing and expected to double sometime during the next century. Climate modelers have predicted that the increase in CO_2 will cause the Earth to warm and precipitation patterns to be altered. Such increases in CO_2 and possible climate change could affect the hydrologic cycle and future water resources. One component of the hydrologic cycle that could be affected is evapotranspiration (*ET*), which could be altered because of the direct effects of CO_2 on stomatal conductance and on plant growth. One important objective of this experiment was to evaluate the effects of elevated CO_2 on the *ET* of wheat.

APPROACH: The evapotranspiration measurements were one component of the much larger Free-Air CO_2 Enrichment (FACE) project, which sought to determine the effects of elevated CO_2 on wheat growth, yield, and many physiological processes, as well as water use. This was the second year of a two-year experiment. Four toroidal plenum rings of 25 m diameter constructed from 12" irrigation pipe were placed in a wheat field at Maricopa, Arizona, shortly after planting. The rings had 2.5-m-high vertical pipes with individual valves spaced every 2 m around the periphery. Air enriched with CO_2 was blown into the rings, and it exited through holes at various elevations in the vertical pipes. Wind direction, wind speed, and CO_2 concentration were measured at the center of each ring. A computer control system used wind direction information to turn on only those vertical pipes upwind of the plots, so that the CO_2-enriched air flowed across the plots, no matter which way the wind blew. The system used the wind speed and CO_2 concentration information to adjust the CO_2 flow rates to attain a near-constant 550 ppm by volume CO_2 concentration at the centers of the rings. Four matching CONTROL rings at ambient CO_2 but with no air flow were also installed the field.

The determination of the effects of elevated CO_2 on *ET* by traditional chambers is fraught with uncertainty because the chamber walls that constrain the CO_2 also affect the wind flow and the exchange of water vapor. Therefore, a residual energy balance approach was adopted, whereby *ET* was calculated as the difference between net radiation, R_n, soil surface heat flux, G_0, and sensible heat flux, H:

$$\lambda ET = R_n - G_0 - H$$

R_n was measured with duplicate net radiometers, and G_0 with soil heat flux plates. H was determined by measuring the temperature difference between the crop surface and the air and dividing the temperature difference by an aerodynamic resistance calculated from a measurement of wind speed. The air temperature was measured with an aspirated psychrometer, and the crop surface temperature was measured with duplicate infrared thermometers (IRTs) mounted above each plot. The net radiometers and IRTs were switched weekly between the FACE and CONTROL plots.

FINDINGS: Figure 2a shows the hourly patterns of weather variables for one mid-season day, April 5, 1994. Foliage temperatures were typically about 3°C cooler than air temperatures except from dawn until about noon. FACE foliage temperatures averaged 1.1°C warmer than CONTROL temperatures on this day.

R_n (fig. 1a) was the largest component of the energy budget of April 5, 1994, generally much larger in magnitude than G_o (fig. 1b) or H (fig. 1c). Consequently, λET (fig. 1d) tended to follow R_n. The error bands on R_n were tight, and differences in R_n between FACE and CONTROL were small (fig. 1a). Consequently, effects of FACE on λET also generally were small although on this particular day, FACE λET averaged 22% less than CONTROL λET.

FACE tended to increase the wheat canopy temperatures by an average 0.63°C from February through April, which made the crop slightly less cooler than air temperature most of the time (data not shown).

Daily FACE R_n averaged 3% less than CONTROL R_n from February through April (data not shown). Furthermore the error bounds were tight with little evidence of changes in treatment effects when the instruments were switched weekly between FACE and CONTROL. Daily totals of G_o were very small (generally < 1 MJ m^{-2} day^{-1}), as expected. Daily FACE H tended to be smaller in magnitude than CONTROL H, which means it was less

negative on most days. This tendency was because the FACE plants were slightly warmer than the CONTROLs most of the time and both FACE and CONTROL plants generally were cooler than the air except from about dawn until noon (fig. 2a).

Daily FACE λET was less than that of the CONTROL plots most of the days (figs. 2b, 2c). At the end of the season in May, the FACE plants matured, earlier leading to larger differences in λET. Excluding these May data, the regression of FACE on CONTROL λET from February through April (fig. 2c) indicates that the FACE treatment decreased λET by an average 8%. The corresponding regression line from 1993 is also plotted in figure 2c showing an average 11% reduction in λET due to FACE for that year. Considering both 1993 and 1994, the results were consistent and indicate about a 10% reduction in λET due to elevated CO_2.

INTERPRETATION: It appears from these data that irrigation requirements for wheat may be somewhat lower in the future high-CO_2 world (provided that any global warming is small).

Also, the observation that FACE caused foliage temperatures to be increased by 0.6°C day and night all season long may be the cause of the accelerated maturity and senescence of the plants in the FACE plots.

FUTURE PLANS: No FACE experiment is planned for 1994-5 but another will commence on about December 1, 1995 (See report on "Progress and Plans for the Free-Air CO_2 Enrichment (FACE) Project."). Micrometeorological parameters required to characterize the growing conditions in support of modeling efforts will be measured. However, because there are now two years' worth of data on the energy balance of wheat under the well-watered condition, we do not plan to repeat this intensive effort in the next experiment.

COOPERATORS: See report on "Progress and Plans for the Free-Air CO_2 Enrichment (FACE) Project."

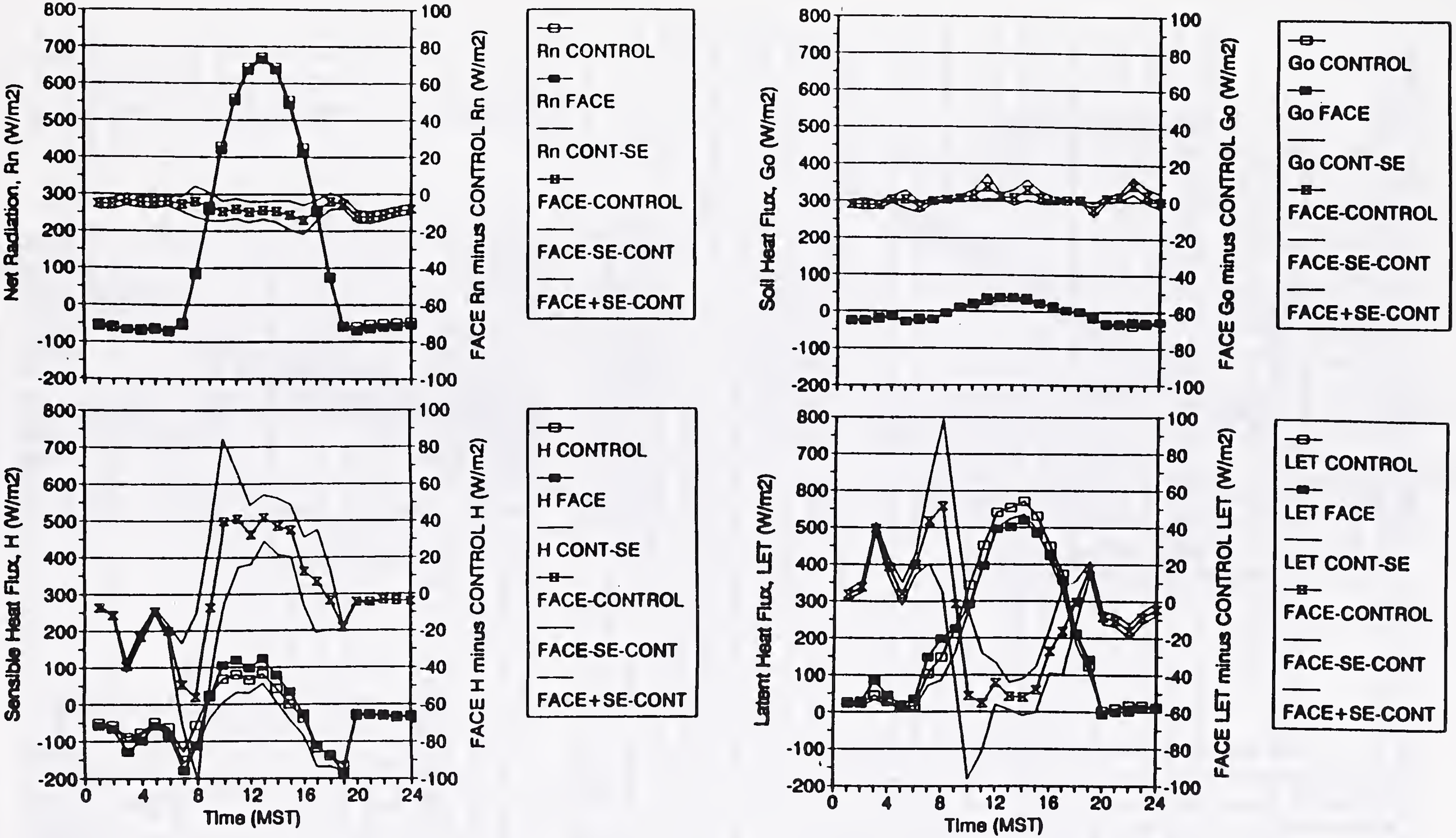
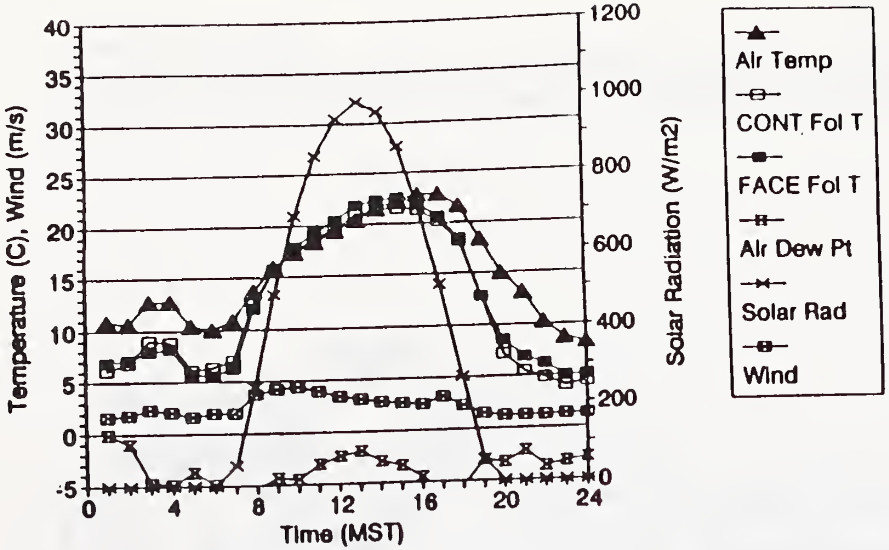
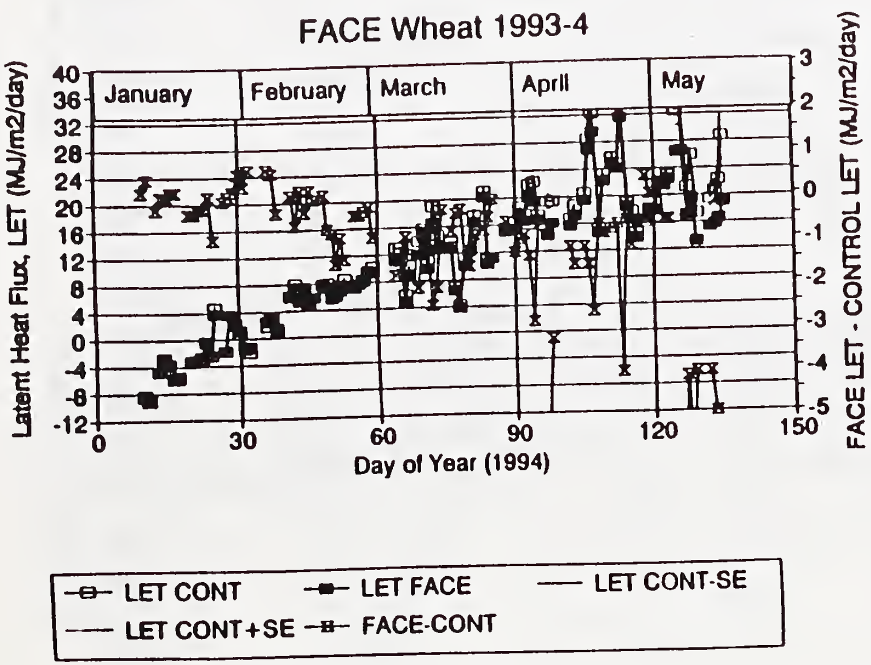


Figure 1. Diurnal patterns of (a) net radiation, (b) soil heat flux, (c) sensible heat flux, and (d) latent heat flux on April 5, 1994 (day-of-year 095), during the 1993-4 FACE Wheat experiment. Also shown on the right axis are the respective differences between FACE and CONTROL plots, as well as some of the standard error bands.





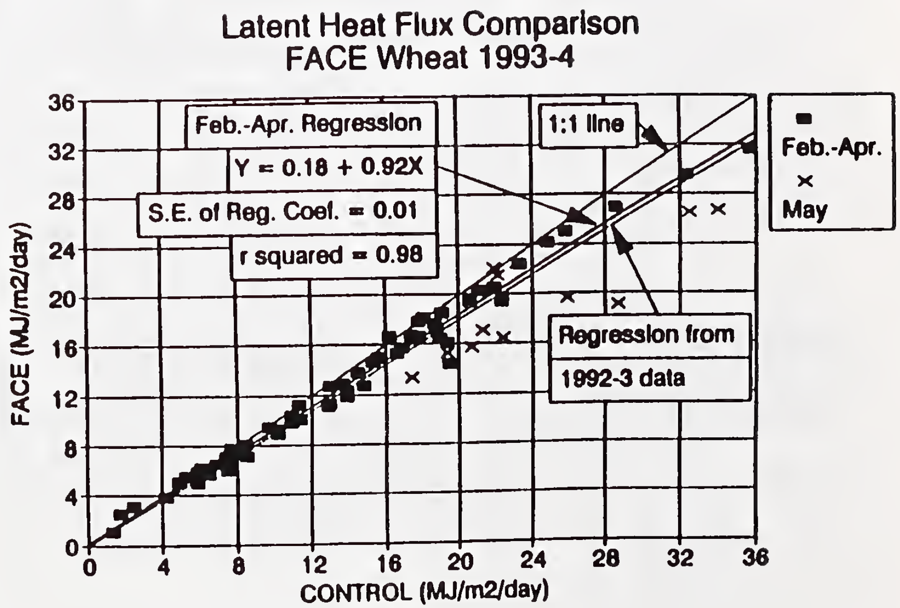


Figure 2a. Diurnal pattern of air temperature, foliage temperature in CONTROL and FACE plots, sir dew point, solar radiation, and wind speed for April 5, 1994.

Figure 2b. Daily latent heat fluxes in the CONTROL and FACE plots and their differences versus day-of-year for the FACE Wheat 1993-4 experiment.

Figure 2c. Daily latent heat flux in the FACE plots versus that in the CONTROL plots for the 1993-4 FACE Wheat experiment. Also shown is the corresponding regression line from the 1992-3 experiment. The regression lines exclude the May data.

DIURNAL TRENDS IN TOTAL WATER POTENTIAL OF LEAVES OF SPRING WHEAT GROWN IN A FREE-AIR CO_2-ENRICHED (FACE) ATMOSPHERE AND UNDER VARIABLE SOIL MOISTURE REGIMES

G.W. Wall, Plant Physiologist; B.A. Kimball, Supervisory Soil Scientist; D.J. Hunsaker Agricultural Engineer; R.L. Garcia, Plant Physiologist; P.J. Pinter, Jr., Research Biologist; S.B. Idso, Physical Scientist; and R.L. LaMorte, Civil Engineer

PROBLEM: Under ample soil moisture, the role of plants in the movement of water through the soil-plant-atmosphere continuum can be thought of as primarily a passive process, in which atmospheric and edaphic conditions play the predominant role. When soil moisture deficits occur, however, a more complicated paradigm unfolds. Plants play an active role in controlling root resistance to water flow from soil to roots. Potential gradients in total water potential (Ψ_W) exist from the bottom to the top of the plant (Denmead and Millar, 1976). Internal resistance to water flow exists throughout the vascular system. Water vapor flow from plant to atmosphere is under direct stomatal control (Ball, 1982). Plants also can adjust the solute concentrations (osmolytes) in their cells to maintain higher levels of turgor potential. Osmotic adjustment (Kirkham, 1990) is a drought tolerance mechanism that enables plants to survive during periods of severe soil water deficits.

In a future high-CO_2 world, water relations in wheat plants may be altered. Unraveling the potential impact of increased atmospheric CO_2 (C_a) on Ψ_W and internal water content of wheat growing under natural open-field conditions is an issue that needs investigation. This study was designed to characterize and quantify the diurnal trends in Ψ_W of wheat leaves grown under high C_a and adequate and reduced levels of soil moisture.

APPROACH: A two-year field study on a hard red spring wheat (*Triticum aestivum* L. cv. Yecora Rojo) crop was conducted in an open field at the University of Arizona, Maricopa Agricultural Research Center, located 50 km south of Phoenix, Arizona (33.1 °N, 112.0 °W). Wheat seeds were sown into flat beds at 0.25-m row spacings. During the 1992-93 season, planting occurred on December 15, 1992 at a plant population of 130 plants m^{-2}, 50% emergence occurred on January 1, 1993, and the crop was harvested May 25-27, 1993. During the 1993-94 season, wheat was sown at a plant population of 180 plants m^{-2} on December 7-8, 1993; 50% emergence occurred on December 28, 1993, and the crop was harvested on June 1, 1994. Following sowing, a FACE apparatus (Hendrey, 1993) was erected on site to enrich the C_a of ambient air ($\sim$350 $\mu L\ L^{-1}$) to a 550 $\mu L\ L^{-1}$ treatment level. A sub-surface drip tape irrigation system supplied a full irrigation (100% evaporative demand) and a 50% reduction in water supply (split-plot) treatment. Preplant application of nitrogen along with several chemigation applications provided a total of 277 and 233 kg ha^{-1} N for the two years, respectively. A preplant application of $\sim$55 kg ha^{-1} P_2O_5 was applied during both years.

Uppermost fully expanded sunlit leaves were excised approximately 5-mm away from the leaf collar and sealed in a plastic bag containing a damp paper towel. Plastic bags containing excised leaves were then stored in a cooler prior to taking measurements of Ψ_W with a Scholander-type pressure chamber (Scholander et al., 1965). Subsampling of 3-4 leaves per treatment over all four replications (means comprised of between 12 and 16 leaves) were taken from predawn until dusk for eight days during 1993 and five days during 1994.

FINDINGS: Early in the season, on day of year (DOY) 43 and 56, 1993 (fig. 1a,b) and DOY 41, 1994 (fig. 2a), values of Ψ_W for only well-watered plants were measured. During this period, the difference in soil matric potential (Ψ_M) between well-watered and water-stressed treatments was negligible. Early in the development of the crop, values of Ψ_W for C_a-enriched plants were significantly less negative than values of Ψ_W for C_a-ambient plants from midday until sunset. When the differential irrigation was initiated, more negative Ψ_W occurred in the water-stressed plants. Evidence of the effect of Ψ_M on values of Ψ_W first appeared on DOY 75 during 1993 (fig. 1d) and DOY 69 during 1994 (fig. 2b). The greatest separation in values of Ψ_W occurred between well-watered and water-stressed plants in 1994 (fig. 2d). During most of the daylight period, C_a-enriched plants had significantly less negative values of Ψ_W than C_a-ambient plants.

INTERPRETATION: Under high C_a, the aperture size of wheat leaf stomata will decrease (Ball, 1982), thereby increasing resistance to water vapor flux. For comparable atmospheric and soil moisture conditions, the transpiration rate per unit leaf area of a C_a-enriched wheat leaf will be lower than that of a leaf growing at present-day ambient C_a. With minimal changes in the size of a C_a-enrichment leaf, total water transport through a C_a-

enriched leaf will also be lower than that for a leaf growing under present-day C_a. Consequently, a leaf growing under higher C_a should have the capacity to maintain higher internal water content throughout the day than a leaf growing at present-day C_a. High internal water content will result in less negative values of predawn, midday, and sunset recovery Ψ_W. Although high C_a induces partial closure of stomata in C_3 plants, a leaf growing in high C_a under water stress may actually maintain its stomata at least somewhat open for a longer period throughout the daylight period than a leaf growing under water stress and present-day ambient C_a. The more negative values of midday Ψ_W in leaves growing under present-day C_a will induce stomatal closure earlier each day as the soil dries, whereas the less negative values of Ψ_W in C_a-enriched leaves will enable stomata to remain open even as the soil becomes more dry. Midday depression in photosynthetic rates, therefore, may be less severe in leaves grown in high C_a, because conductance to CO_2 transfer can be higher throughout a period of water deficit than for leaves growing under present-day C_a levels with closed stomata (Wall, unpublished). Eventually, even a C_a-enriched leaf will close its stomata as a drought conditions become more severe, but the C_a-enriched leaf will have higher overall productivity for a longer period into a drought condition than a leaf grown under present-day C_a. Furthermore, maintaining less negative values of Ψ_W in water-stressed leaves growing under high C_a increases the likelihood that growth of organs will be at near optimal levels even if a soil moisture deficit exists. High C_a, therefore, will enhance the survivability and broaden the nitch where a viable wheat crop can be grown, particularly in the more marginal areas of a dryland agroecosystem.

FUTURE PLANS: A FACE experiment is scheduled for the 1995-96 and 1996-97 growing seasons. The experimental design will have similar CO_2 treatment levels, but the split-plot irrigation treatment will be replaced with nitrogen levels. Although no soil moisture treatment will be imposed during this two-year study, Ψ_W measurements will be made periodically to increase the database for well-watered plants and to determine whether nitrogen has any influence on the plant water relation of wheat under ample soil moisture.

COOPERATORS: Operational support was contributed by the Potsdam Institute for Climate Impact Research, Potsdam, Germany, and by the Carbon Dioxide Research Program of the Office of Health and Environmental Research of the Department of Energy. We also acknowledge the helpful cooperation of Roy Rauschkolb and his staff at the University of Arizona, Maricopa Agricultural Center. The FACE apparatus was furnished by Brookhaven National Laboratory, and we are grateful to Keith Lewin, John Nagy, and George Hendrey for assisting in its installation and consulting about its use. This work contributes to the Global Change Terrestrial Ecosystem (GCTE) Core Research Programme, which is part of the International Geosphere-Biosphere Programme (IGBP). Special thanks is given to Ron Seay who assisted in water potential measurements.

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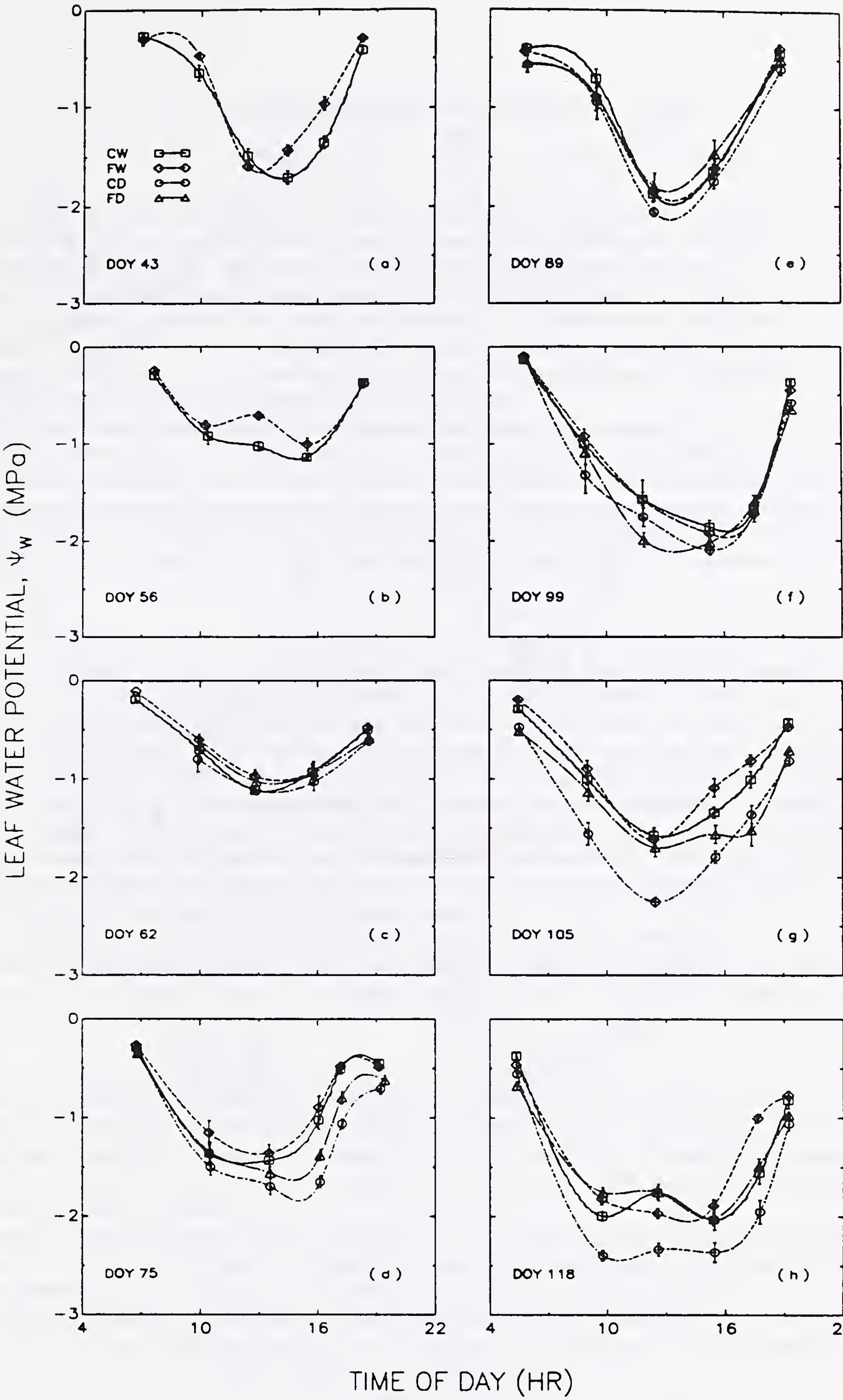

Fig. 1. Diurnal trends in total water potential (Ψ_W) in fully expanded sunlit wheat leaves for day of year (DOY) given during the 1992-93 growing season. Means composed of 3 to 4 leaves for four replications. Error bars given represent one standard error from mean.

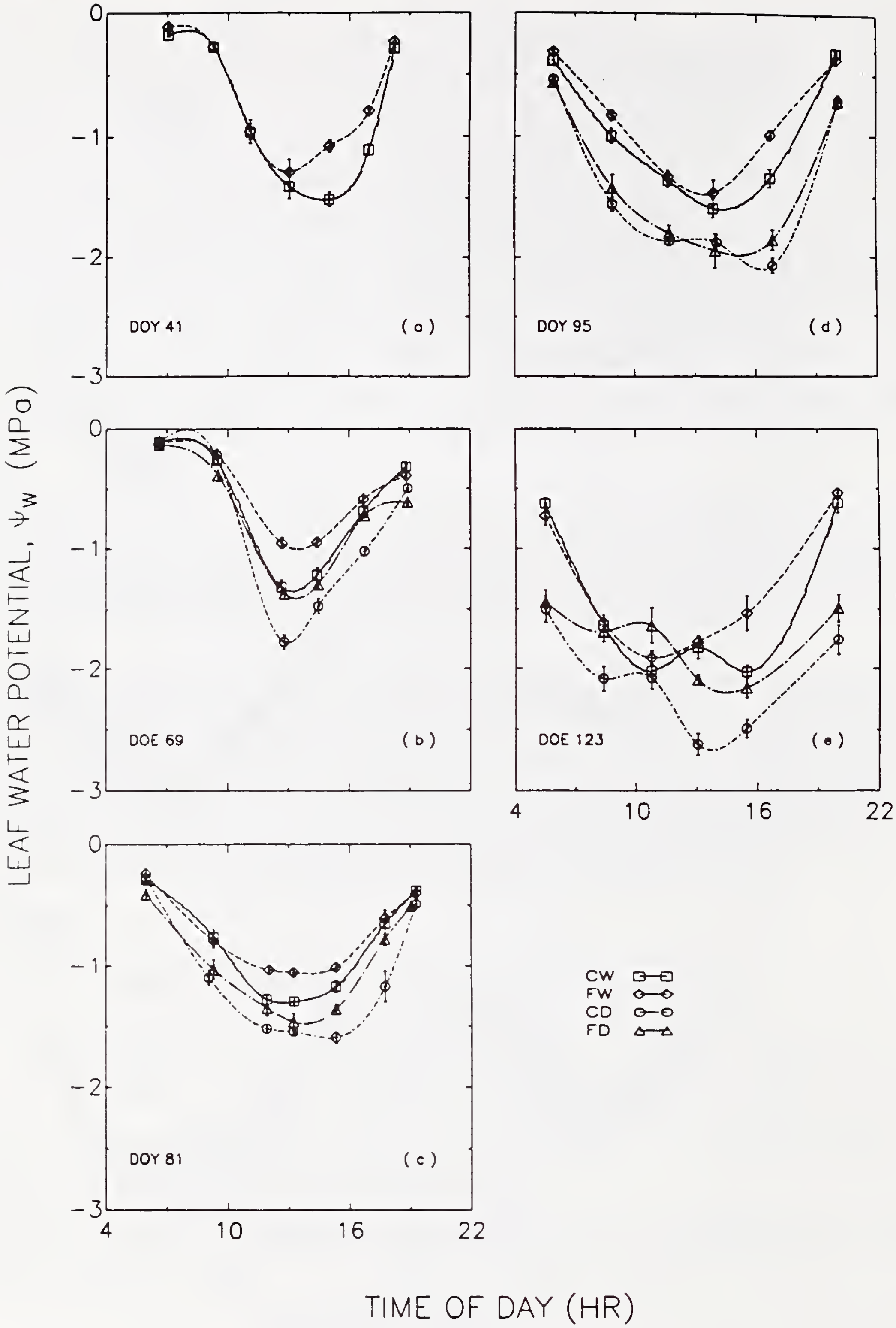

Fig. 2. Diurnal trends in total water potential (Ψ_w) in fully expanded sunlit wheat leaves for day of year (DOY) given during the 1993-94 growing season. Means composed of 3 to 4 leaves for four replications. Error bars given represent one standard error from mean.

CO_2 ENRICHMENT OF TREES

S.B. Idso, Research Physicist; and B.A. Kimball, Supervisory Soil Scientist

PROBLEM: The continuing rise in the CO_2 content of Earth's atmosphere is believed by many people to be the most significant ecological problem ever faced by mankind, because of the widespread assumption that it will lead to catastrophic global warming via intensification of the planet's natural greenhouse effect. However, this belief is largely due to a lack of knowledge of the many beneficial effects of atmospheric CO_2 enrichment on Earth's plant life. Hence, it is imperative that this other aspect of atmospheric CO_2 enrichment be elucidated so that the public can have access to the full spectrum of information about the environmental consequences of higher-than-ambient levels of atmospheric CO_2. Only under such conditions of complete and wide-ranging understanding can the best decisions be made relative to national and international energy policies.

As forests account for two-thirds of global photosynthesis and are thus the primary player in the global biological cycling of carbon, we have chosen to concentrate on trees within this context. Specifically, we seek to determine the direct effects of atmospheric CO_2 enrichment on all aspects of their growth and development and we hope to be able to determine the ramifications of these direct effects for global carbon sequestering, which may also be of considerable significance to the climatic impact of atmospheric CO_2 enrichment, as the biological sequestering of carbon is a major factor in determining the CO_2 concentration of the atmosphere and the ultimate level to which it may rise.

APPROACH: In July 1987, eight 30-cm-tall sour orange tree (*Citrus aurantium* L.) seedlings were planted directly into the ground at Phoenix, Arizona. Four identically-vented, open-top, clear-plastic-wall chambers were then constructed around the young trees, which were grouped in pairs. CO_2 enrichment--to 300 ppm above ambient--was begun in November 1987 to two of these chambers and has continued unabated since that time. Except for this differential CO_2 enrichment of the chamber air, all of the trees have been treated identically, being irrigated at periods deemed appropriate for normal growth and fertilized as per standard procedure for young citrus trees.

In April 1991, eight additional open-top chambers were constructed, into each of which were planted 12 new tree seedlings, including two different species of eucalyptus (*E. microtheca* and *E. polyanthemus*), the Australian bottle tree (*Brachychiton populneum*), a conifer (*Pinus eldarica*), and more sour orange trees. Two of these chambers were maintained at the ambient CO_2 concentration, two at 150 ppm above ambient, two at 300 ppm above ambient, and two at 450 ppm above ambient for the following two years.

Numerous measurements of a number of different plant parameters have been made on the trees of both sets of chambers, some monthly, some bi-monthly, and some annually. Results of our findings are summarized below, along with results of measurements made on some other plants grown in the four large chambers beneath the sour orange trees.

FINDINGS:

(1) Idso and Kimball (45)[1] measured the amount of tissue regenerated from the trunks of the small sour orange trees when they were cut back five different times over the last year of the smaller chambers' two-year operation. For a 75% increase in atmospheric CO_2 from 400 to 700 ppm, aboveground regrowth biomass rose by a factor of 3.2 for these five harvests; while for a 400 to 800 ppm doubling of the air's CO_2 content, it rose by a factor of 3.9.

(2) Idso and Kimball (44) measured the total amount of above ground biomass produced by the Eldarica pine trees growing within the small CO_2 enrichment chambers. At the end of two years of exposure to atmospheric CO_2 concentrations of 408, 554, 680 and 812 ppm, they found that for a 75% increase in ambient CO_2 from 400 to 700 ppm, the trees experienced a growth enhancement factor of 3.4, while for a CO_2 concentration doubling from 400 to 800 ppm, they experienced a growth enhancement factor of 4.2.

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[1] For parenthetical references, see Appendix A, Manuscripts Published or Accepted in 1994.

(3) Garcia, Idso, Wall, and Kimball (29) measured the net photosynthetic rates of the Eldarica pine trees as functions of light intensity. Representing the results with rectangular hyperbolic response curves, they found the light saturated photosynthetic rates of the ambient, +150, +300 and +450 ppm trees to be, respectively, 25, 49, 71, and 78 μmol CO_2 tree^{-1} s^{-1}. Corresponding apparent light conversion efficiencies were 0.05, 0.12, 0.16 and 0.27 μmol CO_2 tree^{-1}/μmol photom m^{-2}.

(4) Garcia, Idso, and Kimball (30) measured the net photosynthetic rates of the Eldarica pine trees as functions of short-term atmospheric CO_2 enrichment to concentrations as high as 3,000 ppm. Rates of the ambient treatment trees saturated at five times their ambient-concentration value, while rates of the highest-CO-treatment trees rose linearly across the entire CO_2 range investigated to more than 10 times their value at 360 ppm.

(5) Idso and Kimball (46) measured total biomass production in 12 different harvests of 3 plantings of a total of 424 *Agave vilmoriniana* plants that grew in the large CO_2 enrichment chambers beneath the sour orange trees over a period of 4 years. The growth enhancement produced by a 300 ppm increase in the air's CO_2 content was found to be a linear function of mean air temperature for this desert succulent, ranging from 28% at 19°C to 51% at 29°C.

(6) Idso and Idso (38) conducted a detailed analysis of several hundred plant carbon exchange rate and dry weight responses to atmospheric CO_2 enrichment that had been published in the scientific literature over the past ten years. They found that the percentage increase in plant growth produced by raising the air's CO_2 content was generally not reduced by less-than-optimal levels of light, water, or soil nutrients, nor by high temperatures, salinity, or gaseous air pollution. More often than not, in fact, the data showed the relative growth-enhancing effects of atmospheric CO_2 enrichment to be greatest when resource limitations and environmental stresses were most severe.

(7) Idso et al. (42) measured net photosynthetic rates of individual leaves of the large sour orange trees that had either been sprayed with methanol or left untreated. No effects of the methanol treatment were evident in any of the measurements. In the trees exposed to the extra 300 ppm of CO_2, however, the upper-limiting leaf temperature for positive net photosynthesis was approximately 7°C higher than it was in the ambient-treatment trees. This phenomenon led to a 75% enhancement in the net photosynthesis of the CO_2-enriched trees at a leaf temperature of 31°C, a 100% enhancement at a leaf temperature of 35°C, and a 200% enhancement at 42°C.

(8) Idso and Kimball (43) summarized the major results of six years and three months of continuous CO_2 enrichment of four sour orange trees to 300 ppm above the nominal ambient concentration of 400 ppm at which four control trees are maintained. Figure 1 shows that at the end of this period, the standing trunk plus branch volume of the CO_2-enriched trees was approximately twice that of the ambient-treatment trees, while the total fruit rind volume produced by the enriched trees over four consecutive harvests was about three-and-a-third times that produced by the ambient trees. Figure 2 shows that it took almost two years for the maximum "aerial fertilization effect" of the elevated CO_2 to manifest itself and that it has maintained itself at a total biomass-enhancing factor of about 2.7 for over four years now.

INTERPRETATION: The implications of our findings have a direct bearing on the current debate over anthropogenic CO_2 emissions. They demonstrate that CO_2 is an effective aerial fertilizer, enhancing plant growth under nearly all conditions.

FUTURE PLANS: We anticipate continuing the sour orange tree experiment for several more years, focusing on the effects of atmospheric CO_2 enrichment on fruit production. We also plan to study CO_2 effects on a number of other plants.

COOPERATORS: Institute for Biospheric Research; U.S. Department of Energy, Atmospheric and Climate Research Division, Office of Health and Environmental Research.

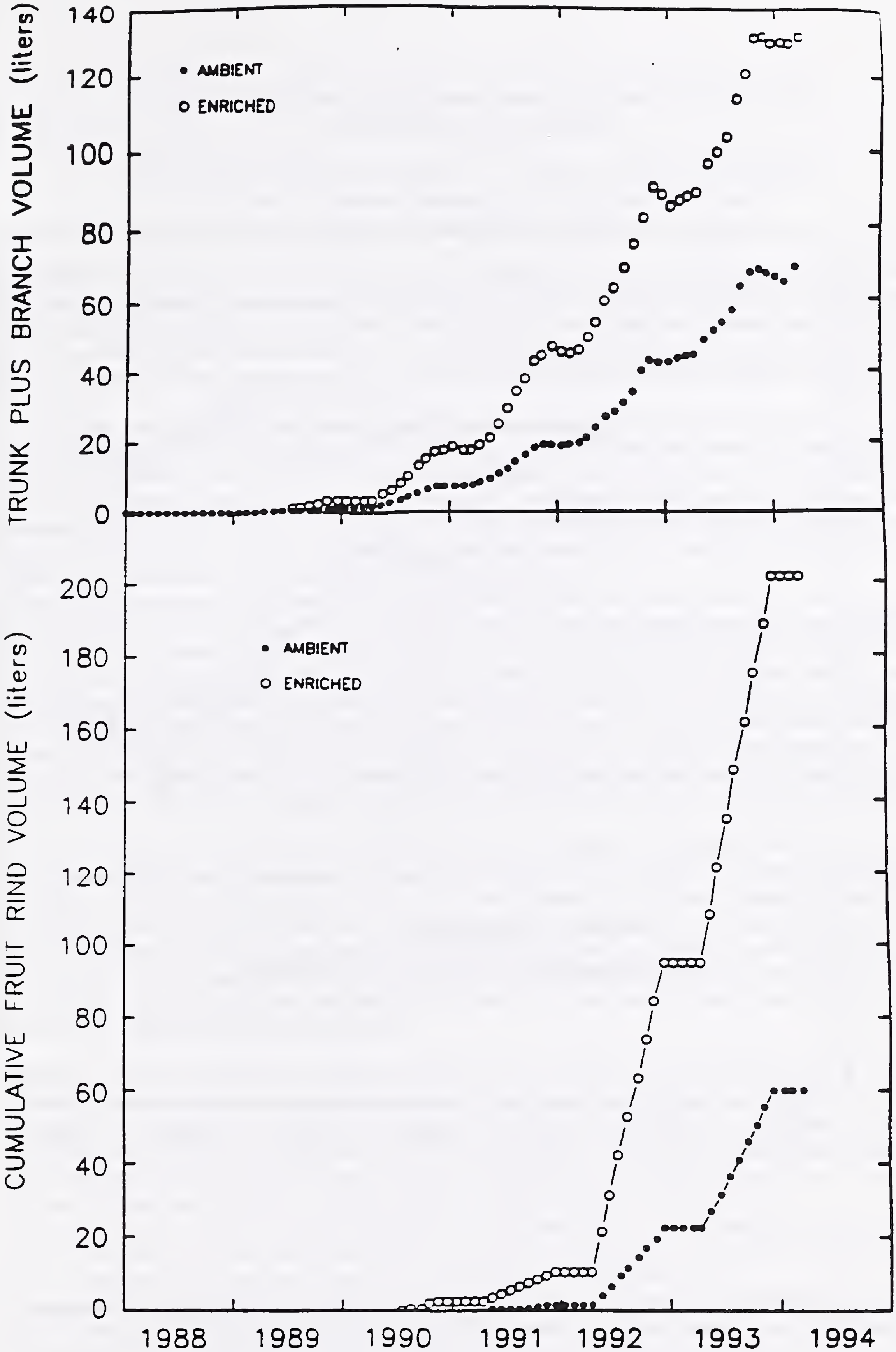

Figure 1. Six-plus years of trunk plus branch volume trends of the CO_2-enriched and ambient-treatment trees (upper panel) and four-year trends of their cumulative fruit rind volumes (lower panel).

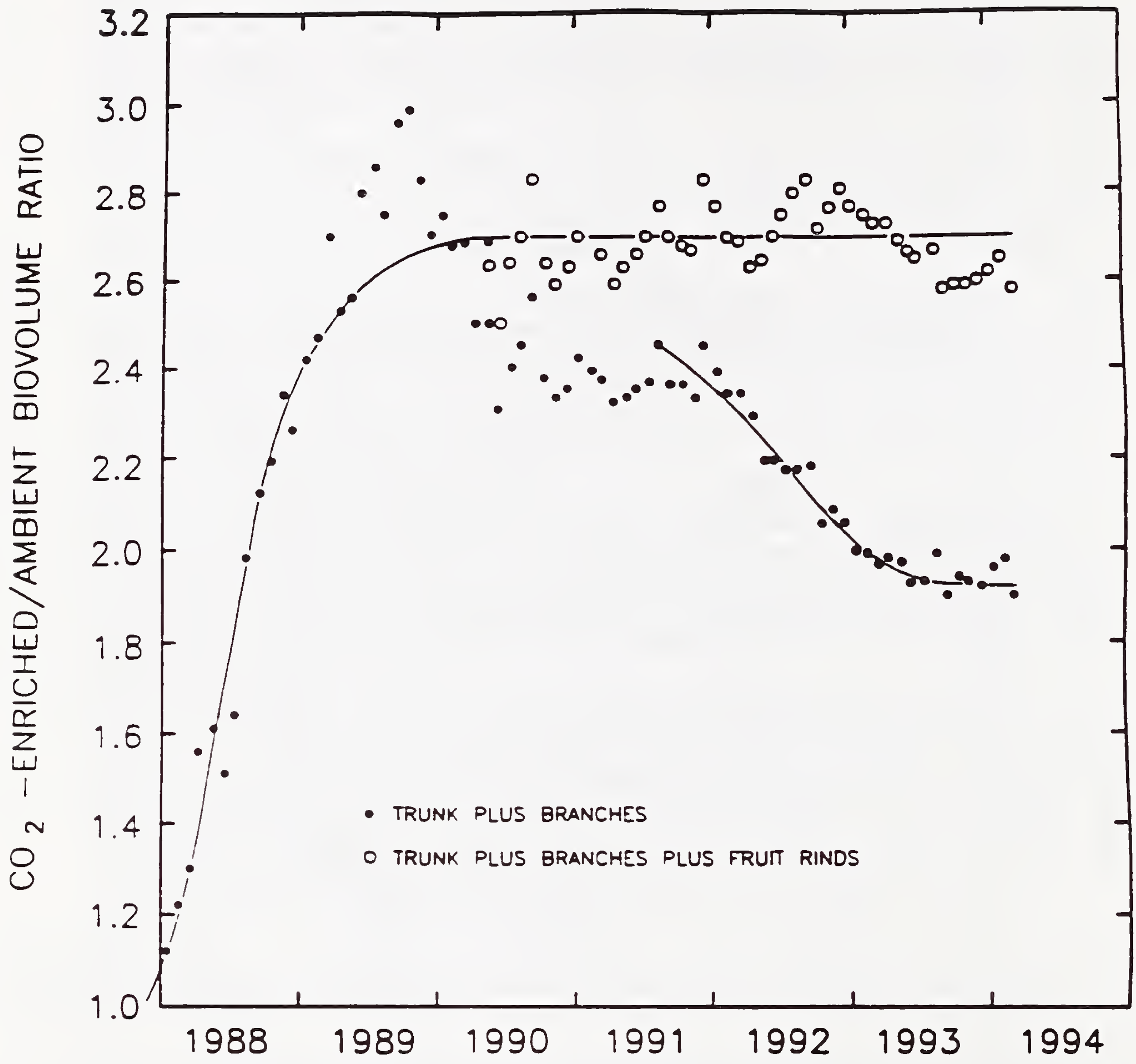

Figure 2. The long-term trend of the CO_2-enriched/ambient-treatment ratio of trunk plus branch volume and the long-term trend of the similar ratio of trunk plus branch plus cumulative fruit rind volume.

WHEAT EVAPOTRANSPIRATION UNDER CO_2 ENRICHMENT AND VARIABLE SOIL MOISTURE

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P.J. Pinter, Jr., Research Biologist; G.W. Wall, Plant Physiologist;
and R.L. LaMorte, Civil Engineer

PROBLEM: The Earth's rising atmospheric carbon dioxide (CO_2) is expected to impact agricultural production worldwide. One concern is how increased CO_2 will affect crop evapotranspiration (ET), which, in turn, could affect future agricultural water use and management. To date, only a few research studies have been attempted which sought to quantify the effects of elevated CO_2 on crop ET in agricultural fields. Our objective was to evaluate the effects of elevated CO_2 and irrigation quantity on the ET of wheat using soil water depletion measurements.

APPROACH: The free-air CO_2 enrichment (FACE) facility at The University of Arizona, Maricopa Agricultural Center allows study of the effects of elevated CO_2 on crops cultivated in an environment representative of future agricultural fields. In December 1993, the second FACE wheat experiment commenced with planting of Yecora Rojo, a spring wheat cultivar, in rows spaced 0.25 m apart. As in earlier studies, the FACE technique was used to enrich four, circular plots, 25 m in diameter, to a CO_2 concentration of 550 μmol mol^{-1} (FACE plots). Four matching CONTROL plots, with no CO_2 enrichment, were also installed in the field. Other details on the FACE system are provided in the 1992, and 1993, USWCL Annual Report.

The FACE experimental design was a strip-split-plot with CO_2 the main effect, replicated four times. Each of the eight circular plots were split into two semicircular subplots with each subplot receiving either a well-watered ($\sim$100% ET replacement) or water-limited ($\sim$50% ET replacement) irrigation treatment, designated WET and DRY, respectively. All treatments were given 30 mm of water applied by a portable sprinkler system immediately after planting to adequately moisten the seed bed. Following crop establishment, wheat subplots were irrigated with a subsurface drip system installed 0.18-0.25 m below the soil surface with 0.5-m spacings between drip tubes. Irrigation scheduling for the WET treatment subplots was determined by a meteorologically-based crop water use model (AZSCHED), developed by The University of Arizona, Agricultural and Biosystems Engineering Department. DRY subplots received the same irrigation quantity as the WET subplots, but only on every other irrigation of the WET.

Soil water contents were measured in all subplots on 46 days between 9 December 1993, and 26 May 1994. Time-Domain-Reflectometry equipment was used to measure soil water content in the top 0.3-m soil profile. Subsurface soil water contents (from 0.4 m to 2.0 m) were measured with a neutron scattering device in 0.2-m increments. Typically, soil water contents were measured in the mornings, prior to an irrigation and again two days after the irrigation. Crop ET was measured by the change in soil water over the active rooting depth between two sampling dates. Only sampling periods when water was not added by irrigation or rainfall were used for ET measurement. However, ET was estimated for periods when irrigation or rainfall occurred from the ET measurements made before and after the period.

FINDINGS: Water applied from irrigation (including the initial 30 mm for crop establishment) totaled 630 mm for the WET and 290 mm DRY irrigation treatments. Total seasonal rainfall was about 60 mm. All treatments had similar soil water contents over a 0.9-m soil profile through February 1994 (fig.1). Differences in soil water contents between WET and DRY treatments began about late February and persisted through the remainder of the season. FACE water contents were slightly higher than CONTROL within the WET irrigation treatment, however, considerably lower than CONTROL within the DRY treatment for much of the season.

Daily ET under DRY irrigation (fig. 2a) was similar for CO_2 treatments in 1994. Daily ET under WET irrigation (fig. 2b) was similar for FACE and CONTROL from January through April 1994; and considerably lower for FACE in May due to the accelerated maturity of the plants in the FACE plots.

Seasonal accumulated ET (table 1) was nearly equal for FACE and CONTROL under DRY irrigation, but was about 5% lower for FACE than CONTROL under WET irrigation treatments. However, CO_2 effects on ET were not statistically significant at the 0.05 level of probability. Differences between WET and DRY irrigation treatments were significant ($p < 0.05$).

INTERPRETATION: Under both well-watered and limited-water irrigation managements, elevated CO_2 concentration (550 μmol mol^{-1}) appears to have very little effect on wheat evapotranspiration, as determined by soil water depletion. This result was the same as that determined in the FACE wheat experiment of 1992-93 using similar procedures.

FUTURE PLANS: A third FACE wheat experiment is planned for the 1995-96 season, with soil fertility instead of irrigation as the subplot effect. ET will again be determined from soil water measurements.

COOPERATORS: See FACE cooperator listing in the 1994 USWCL Annual Report entitled "Effects of free-air CO_2 enrichment (FACE) on the energy balance and evapotranspiration of wheat," by B.A. Kimball.

Table 1. Accumulated seasonal ET (mm) of wheat for 137 days (10 January to 25 May 1994).

	DRY	WET	DRY/WET
Control	435a	659b	0.660
Face	439a	623b	0.705
Face/Control	1.009	0.945	

ab Means followed by same letter in row or column are not significantly different at the 0.05 probability level.

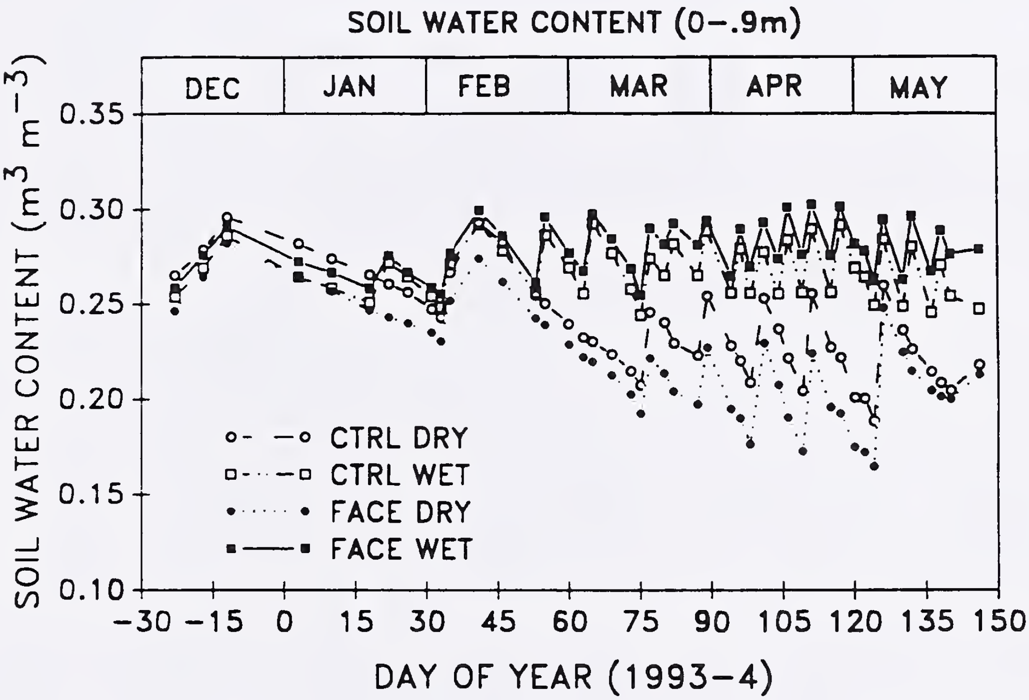

Figure 1. Soil water contents (0 to 0.9-m soil profile) with day of year for CONTROL DRY (CTRL DRY), CONTROL WET (CTRL WET), FACE DRY, and FACE WET treatments in 1993-94. The values are the mean of the four replicates.

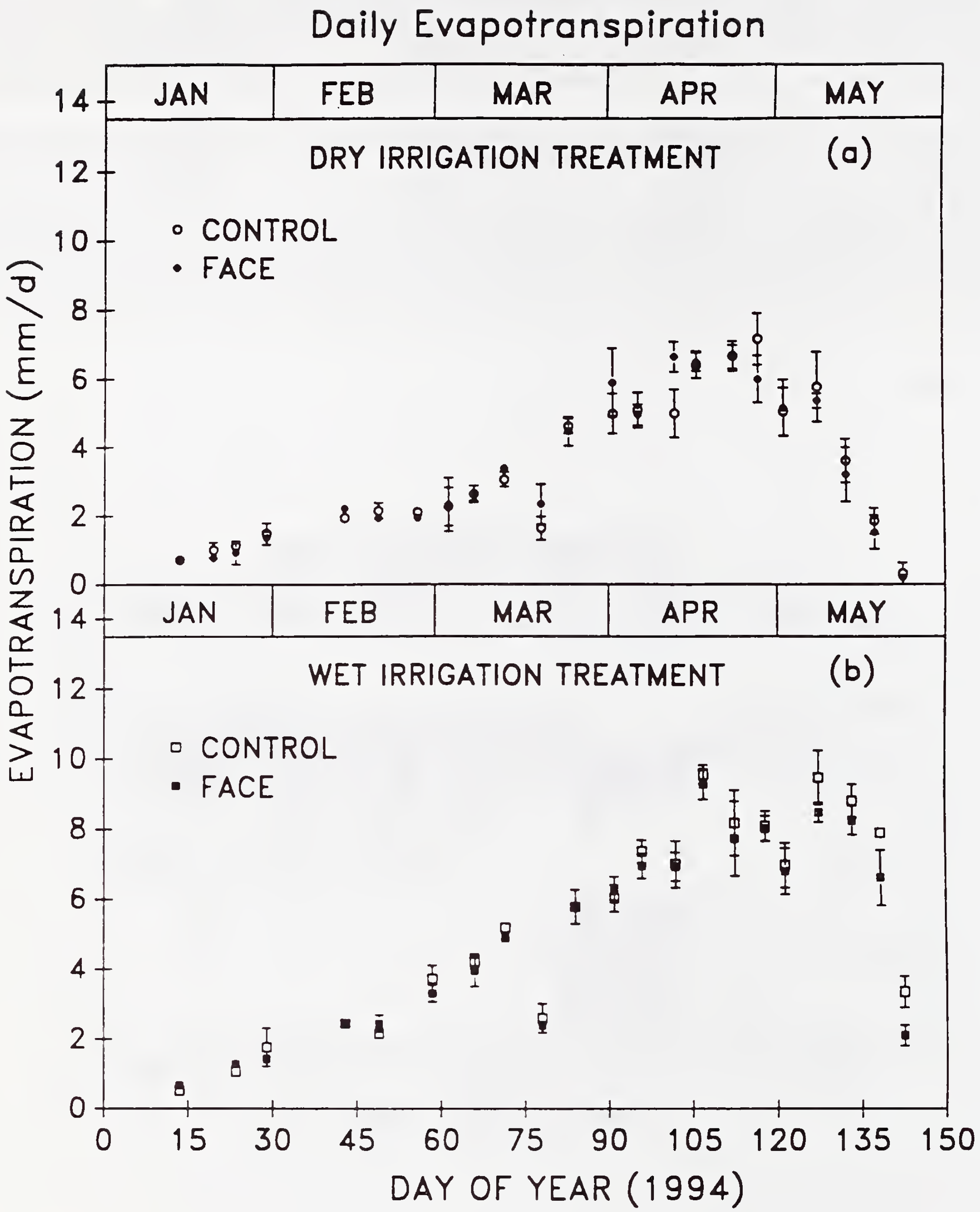

Figure 2. Soil water balance estimates of daily evapotranspiration for CONTROL and FACE treatments under DRY (a) and WET (b) irrigation in 1993-94. Data values are the mean plus and minus one standard error of the four replicates.

EVALUATING PLANT DYNAMICS AS RELATED TO WATER CONSERVATION AND CLIMATE CHANGE USING REMOTE SENSING

THE SCALING CHARACTERISTICS OF REMOTELY SENSED VARIABLES FOR SPARSELY-VEGETATED HETEROGENEOUS LANDSCAPES

M.S. Moran, Physical Scientist; and P.J. Pinter, Jr., Research Biologist

PROBLEM: With recent advances in airborne and satellite-based sensors for mapping regional and global energy balance, there is interest in aggregating remotely sensed variables (and surface energy fluxes derived from these variables) from local to regional scales. This interest is due to the desire to 1) apply local-scale approaches with regional-scale data, and 2) validate results of regional-scale methods by comparison with results of local-scale methods. These goals require investigation of methods for both aggregation of remotely-sensed variables (particularly, radiometric temperature and reflectance, T_r and ρ) and aggregation of energy balance components (particularly, sensible and latent heat flux, H and λE). There is considerable uncertainty involved in aggregating such data over large areas. This uncertainty is directly related to two factors: 1) the nonlinearity of the relation between the sensor signal and T_k, H or λE, and 2) the heterogeneity of the site.

APPROACH: This study addressed the issues of aggregation related specifically to heterogeneous landscapes at local and regional scales. For this analysis, spectral data from four sensors mounted on four different platforms were acquired at the Walnut Gulch Experimental Watershed (WGEW) near Tombstone, Arizona. The platforms, sensor characteristics, locations of ground targets, and dates of data acquisition are summarized in table 1. Based on several sets of spectral images with spatial resolutions ranging from 0.3 m to 120 m, we studied the effects of aggregation by computing remotely sensed variables and energy balance components in two ways. First, the variable (e.g., H) was computed from the radiance at the pixel resolution (e.g., 120 m) and these values were averaged to obtain a value of H at a coarser resolution (e.g., 1 km). Second, pixel-resolution values of radiance were averaged to the coarser scale, and then a value of H was computed. The difference between these two computations of H revealed the error due to nonlinearities in the relation between surface radiance and H.

FINDINGS: Results showed that the error in the aggregation of T_k and ρ was negligible for a wide range of conditions. However, the error in aggregation of H and λE was highly influenced by the heterogeneity of the site. For example, we aggregated data from two sites with varying surface roughness conditions: a shrub-dominated and a grass-dominated site. The surface roughness (z_o) of the shrub-dominated site was 0.04 m and z_o of the grass-dominated site was 0.01 m. Then, we computed the data aggregation in three ways: 1) H computed with a variable z_o value related to shrub or grass cover, 2) H computed with a constant z_o=0.04m, and 3) H computed with a constant z_o=0.01m. In this way, we could investigate the variability in H associated with the variability in z_o. For thermal scanner data with fine resolution (0.3 m), there were large differences (nearly 50 W m^{-2}) between values of H aggregated with differing z_o values, especially in mid-afternoon (fig. 1). There was negligible error (< 5 W m^{-2}) associated with measurements in the early morning when values of H were small ($\simeq$ 35 W m^{-2}). For NS001 data with moderate resolution (6.0 m), the error in aggregation of H was smaller (< 25 W m^{-2}) (fig. 2) than for the higher-resolution thermal scanner data.

Based on further analysis of the differing spatial-, temporal-, and radiometric-resolution data listed in table 1, we found errors in H larger than 50% due simply to data aggregation. The conditions associated with the largest aggregation errors in H were:

- sites that are composed of a mix of stable and unstable conditions;
- sites that have considerable variations in aerodynamic roughness, especially for highly unstable conditions where the difference between surface and air temperature is large; and
- sites that are characterized by patch vegetation, where the pixel resolution is less than or nearly equal to the diameter of the vegetation "element" (in most cases, the diameter of the dominant vegetation type or vegetation patch).

Thus, knowledge of the surface heterogeneity is essential for minimizing error in aggregation of H and λE.

A scheme was presented for quantifying surface heterogeneity as a first step in data aggregation. This method utilized a scattergram of the NDVI versus surface-air temperature (T_k-T_a) from the spectral image. This scattergram is plotted within a theoretical trapezoidal shape (termed the Vegetation Index/Temperature [VIT] trapezoid) that is computed from on-site meteorological data and the Penman-Monteith equation (Moran et al., 1994a). The left edge of the VIT trapezoid was related to conditions of potential evapotranspiration, and the right edge was related to conditions in which λE=0. Thus, the location of the image data within the VIT trapezoid provides information

about the variability of H and λE, in addition to the basic information on variability of the vegetation index and T_k-T_a. The VIT Trapezoid was computed for WGEW for DOY 156 and 252. The yoke-based data illustrated the variability at sub-element scale (0.3 m resolution < plant diameter) and the TM data illustrate variability of mixed pixels (120 m resolution > > plant diameter). For DOY 156 (dry season), the yoke and TM data were clustered in the lower right corner of the VIT Trapezoid, indicating low vegetation cover and dry conditions (fig. 3a). For DOY 252, the yoke and TM data were shifted toward the left edge of the trapezoid, indicating higher λE values associated with the wet season (fig. 3b). The general variability of NDVI and T_k-T_a was much greater than for DOY 156 at both resolutions.

INTERPRETATION: This study emphasized the need to account for site heterogeneity in selection of a scheme for aggregation of surface energy balance components. This is particularly true for sparsely-vegetated sites, such as the Walnut Gulch semiarid rangeland. However, the quantification of site heterogeneity is not an easy task since it can be related not only to vegetation cover but also to time of day, time of year, and sensor spatial resolution. Thus, it is important to understand the sources of nonlinearity in the computation of H and λE in order to understand the errors associated with aggregation.

FUTURE PLANS: Future work should address two issues. First, this analysis addressed only scale issues related to surface heterogeneity. It did not address feedbacks and integrating effects of the atmosphere that could decrease the potential for error in aggregation that was indirectly illustrated in figure x. Second, results from this analysis showed that there was substantial error in aggregation of H for sites with differences in surface roughness. These results were obtained with the aggregation of sites where roughness varied by only 0.03 m. The aggregation error for sites with greater variation in roughness lengths, such as mixtures of grassland and forest, could be many times larger than that presented here.

COOPERATORS: K.S. Humes, ARS Hydrology Laboratory, Beltsville, MD.

Table 1. General description of instruments deployed during the Monsoon'90 Experiment.

PLATFORM	INSTRUMENT	NO. OF BANDS	WAVELENGTH RANGE	TARGETS	FLIGHT DATES (DAY OF YEAR 1990)
Yoke	Exotech Radiometer, IFOV: 15° Everest IRT, IFOV: 15° Footprint: 0.3 m	4 1	0.50-0.89 μm 8-13 μm	Kendall: 0.48x0.12 km Lucky Hills:0.12 x 0.12 km	156, 252
Cessna	Thermal Infrared Scanner: IFOV 2.4 mrad Footprint: 0.2 m at 0.09 km AGL 1.7 m at 0.92 km AGL 6.0 m at 3.35 km AGL	1	8-12 μm	Kendall and Lucky Hills: 380 pixels by 480 lines	209, 221 @ 0.09 km AGL 222 @ 0.92 km 209 @ 3.35 km
C-130	NS001 Thematic Mapper Simulator, IFOV: 2.5 mrad Footprint: 6.0 m	8	0.46-12.3 μm	All 8 METFLUX Sites: approximate size 380 pixels by 480 lines	221
Landsat-5	Thematic Mapper (TM) Footprint: 30 m Reflected and 120 m Emitted	7	0.45-12.5 μm	Two targets: WGEW and RIP (Riparian site) 10 km by 3 km each	156, 252

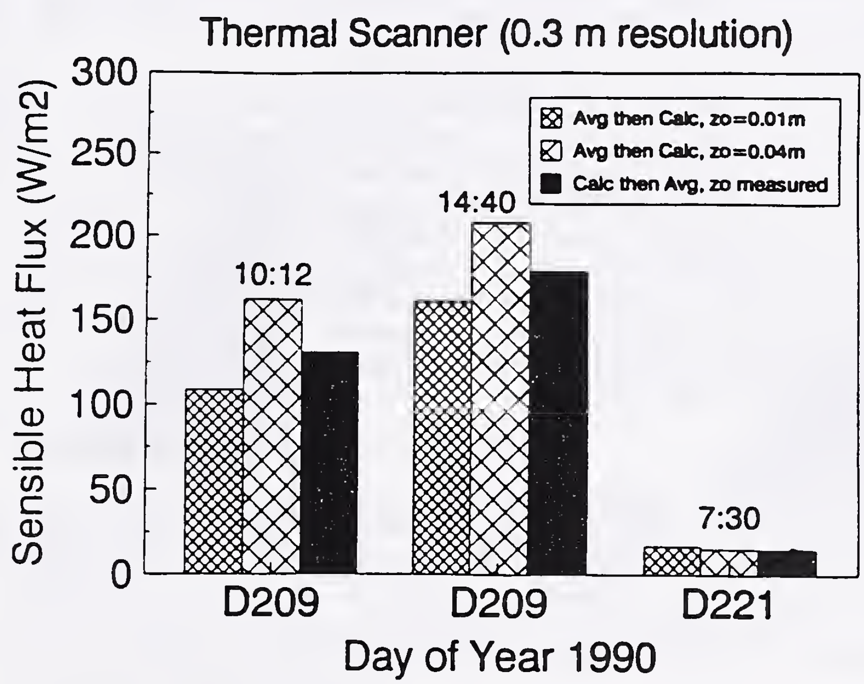

Figure 1. An investigation of the effect of site-specific differences in z_o on estimates of sensible heat flux (H) using thermal scanner data. z_o was assumed to 0.01 m at grassland sites and 0.04 m at shrub-dominated sites for the bars labeled "z_o measured."

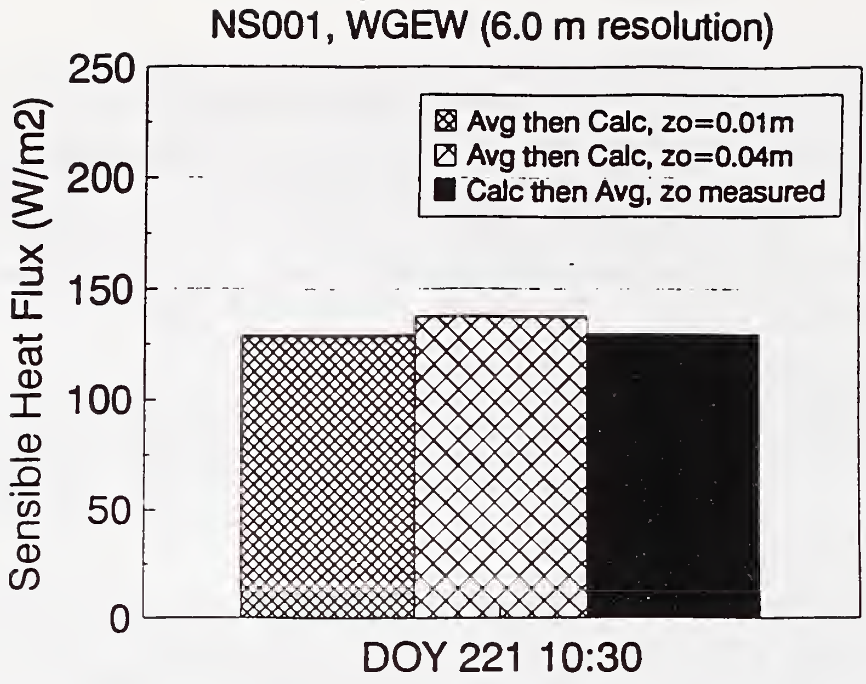

Figure 2. An investigation of the effect of site-specific differences in z_0 on estimates of sensible heat flux (H) using NS001 data. z_0 was assumed to be 0.01 m at grassland sites and 0.04 m at shrub-dominated sites for the bar labeled "z_0 measured."

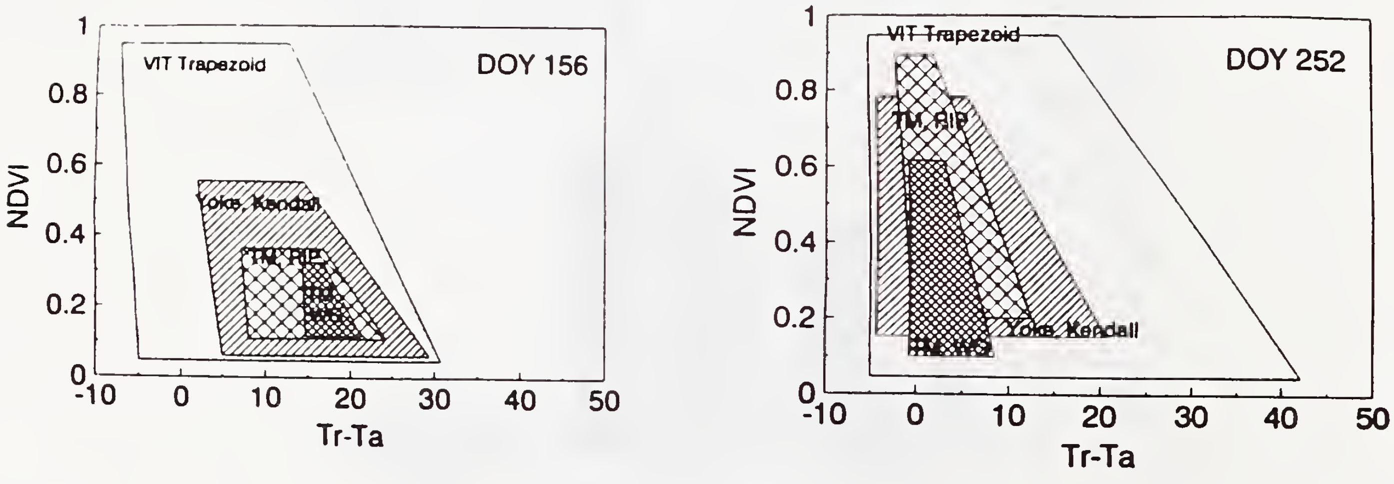

Figure 3. An illustration of the variability of the yoke-based (0.3 m resolution) and TM spectral data (120 m resolution) for WGEW on DOYs 156 and 252.

CHANGES IN HIGH RESOLUTION REFLECTANCE SPECTRA OF COTTON LEAVES CAUSED BY WHITEFLY HONEYDEW

P.J. Pinter, Jr., Research Biologist

PROBLEM: The silverleaf whitefly (*Bemisia tabaci* L.) poses a serious threat to cotton and high value vegetable crops in western states. Responding to the increasing risk that this insect poses to agriculture, ARS has developed a 5-Year National Research and Action Plan for its management and control. Promising integrated pest management (IPM) measures include biological control with parasitic wasps, breeding for host plant resistance, and use of trap crops, and modification of cultural practices to reduce population buildup. Remote sensing has potential for supporting IPM efforts through early identification of favorable conditions for whitefly colonization and by detecting the presence of damaging populations so that appropriate control measures can be initiated. Remote sensing techniques can also provide tools for entomologists and plant scientists to quantify crop stress and insect-plant interactions in a rapid, efficient manner.

Recognizing the presence of whiteflies in a crop canopy using conventional remote sensing techniques is difficult because their size precludes direct observation. Populations have to build to rather high levels and cause changes in canopy color or leaf biomass before detection becomes feasible. By that point however, considerable economic losses may have already occurred, so emphasis should be directed towards preventative measures. Identification of favorable conditions for whitefly oviposition, growth, and development is critical for effective IPM. However, biologists still do not know whether colonizing adults utilize chemical, thermal, or visual clues when infesting new fields. Horticulturists have long suspected that whiteflies are initially attracted to a plant by its color and have noted that whiteflies seem to have varietal preferences within a plant species. There are specific color recommendations for whitefly traps and even for clothing of nursery workers so that the passive transport of these pests from one greenhouse to another is minimized. These observations and practices all suggest that visual clues are very important to whiteflies when colonizing a new field. Field observations and research indicate whitefly populations are often higher in water-stressed crops. In as much as water stress increases plant temperatures and alters canopy reflectance, remotely-sensed observations in the thermal and reflected solar region of the spectrum may help to identify incipient outbreak sites. Pesticide applications or parasite releases could then be targeted to specific fields or susceptible areas within a field. Preventative measures might include modifying irrigation regimes or soil amendment/tillage practices to avoid whitefly problems. Alternatively, if certain features of high resolution spectral reflectance data from single leaves were found to correlate with whitefly preference, that information might prove useful to geneticists trying to incorporate resistance in new lines.

Detection of some crop pests is enhanced when they produce a byproduct that alters the reflectance of the host canopy. Such is also the case with whiteflies. As the immatures feed on the abaxial surfaces of plant leaves, they spray honeydew almost continuously over the upper surfaces of leaves that are deeper in the canopy. This produces a shiny patina on the leaves that is particularly obvious to an observer of the canopy under some sun angle and viewing direction combinations. Honeydew-tainted cotton fibers command lower prices on the market because it interferes with the ginning process. With time and the right microclimatic conditions, the honeydew can also support actively growing colonies of a black fungus (*Aspergillus sp.*). Preliminary research described here examines the possibility of detecting whitefly infestations indirectly from the altered spectral reflectance characteristics of honeydew covered leaf surfaces.

APPROACH: High resolution spectral radiance of the adaxial leaf surfaces of cotton plants (*Gossypium hirsutum* L.) was measured *in vivo* under natural solar illumination using a Spectron SE-590 spectroradiometer (nominal 15°fov, 350 to 1100 nm) and converted to reflectances via frequent measures of a painted $BaSO_4$ standard. Leaves were selected visually from cotton plants that were grown in a glasshouse where whitefly populations were very high. Measured targets included 1) normal appearing green leaves; 2) leaves covered with varying amounts of freshly deposited, shiny honeydew; 3) leaves with old deposits of honeydew that had become covered with a dark, furry *Aspergillus* fungus; and 4) chlorotic leaves.

Each fully expanded leaf was held relatively flat in a circular, wire clamp and positioned under the spectroradiometer lens without detaching it from the plant. The viewing axis of the spectroradiometer was maintained at 45° relative to the angle of direct beam solar incidence. Leaf angle was rotated in 10° increments in the principal plane of the sun from -40° through +20° degrees relative to the viewing angle of the spectroradiometer. An angle of -22.5° thus represented maximum forward scattering of direct beam solar

illumination. In practice, the uneven surface of the leaf blades precluded precise positioning of leaf angle. In order to simulate the effect of leaves near the top of a uniform vegetation canopy, an illuminated green grass background was held constant throughout all measurements. Absolute reflectance data were biased to the extent that transmitted light was not accounted for. However, relative differences among targets at a given view angle, and among view angles for a given target, were representative of what might be expected in the field.

After the first series of view angle measurements, leaves were washed with 5 ml of distilled water, permitted to air dry, and measured at all view angles a second time. At the end of the spectral measurements, leaves were clipped from the plant and measured on an optical planimeter. Washings were analyzed for total sugars. Sugar concentrations were expressed on a per-unit-leaf-area basis.

FINDINGS: Representative spectral reflectances from different types of leaves are shown in figures 1a and 1b. Chlorotic leaves displayed the highest reflectance in all spectral regions. The *Aspergillus*-covered leaves had the lowest average reflectance between 500 and 600 nm and in the near infrared (NIR, >700 nm) but were brighter than normal green leaves in the region normally dominated by chlorophyll absorption. In contrast, leaves with honeydew displayed slightly higher reflectances in the blue, red, and NIR regions, and appeared almost identical to normal leaves near the green reflectance peak (~540 nm). The position of the red edge (*i.e.*, the abrupt reflectance transition between the visible and NIR regions) appeared unaffected by the presence of honeydew in very heavy concentrations.

When normal green leaves without honeydew were viewed from off-nadir angles, bidirectional reflectance factor (BRF) properties were evident (fig. 2a). Compared with the 0° viewing angle, reflectance spectra increased as much as 40 to 60% in the visible and about 10% in the NIR in the forward scattering direction (*i.e.*, negative view angles). At positive view angles, reflectances decreased by a similar amount.

Honeydew was responsible for even larger variations in BRF (fig. 2b). The percentage changes in this figure were computed relative to spectra of the same leaf taken at the same view angle after washing to remove the honeydew. Thus most of the BRF seen in figure 2b were due to the honeydew. These data illustrate the "mirror" effect one observes when viewing a leaf with honeydew in the forward scattering direction. There was also a high degree of spectral dependency in these data. Honeydew caused an increase of as much as 300% in the blue and red, 150% in the green, but only 10% to 20% in the NIR. A reduction in BRF was noted in the backscattering direction, and the wavelength dependent features were suppressed.

INTERPRETATION: These data indicate that whitefly honeydew has a profound effect on BRF characteristics of cotton leaves and suggests a means for indirectly detecting the presence of whiteflies in the field. The honeydew effect was most noticeable in the forward scattering directions and appeared qualitatively correlated with the amount of honeydew on the leaves. Inasmuch as the honeydew-induced changes in BRF were wavelength dependent, off-nadir sensors on aircraft or satellite platforms offer an intriguing potential for assessing the extent of whitefly infestations for IPM. Because honeydew residues on cotton seriously affect lint quality and ginning operations, knowledge that a particular field was affected by whiteflies may influence price and even marketability of the lint.

FUTURE PLANS: Multispectral reflectance and thermal imagery acquired from overflights at MAC during the summer of 1994 will be examined in light of these findings.

COOPERATORS: Hollis Flint and Don Hendrix, USDA, ARS, Western Cotton Research Laboratory.

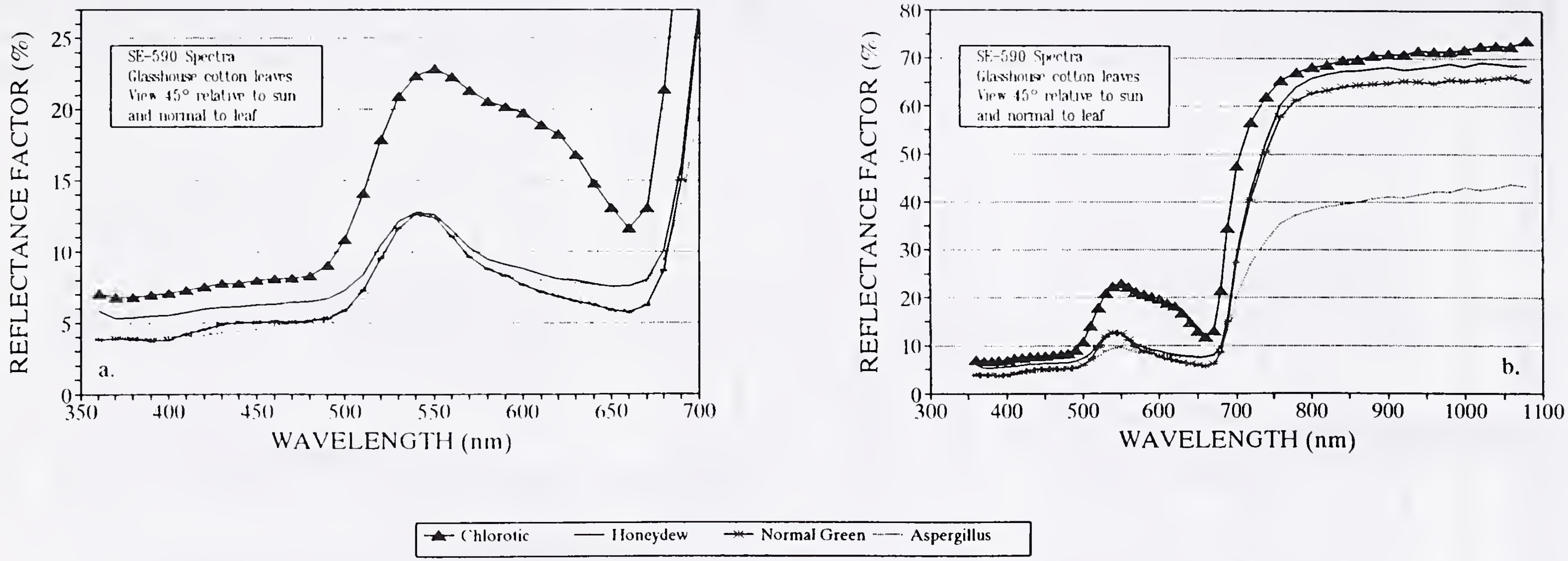

Figure 1. High resolution reflectance spectra of cotton leaves acquired with SE-590. Spectra are from the adaxial surfaces of 1) a chlorotic leaf; 2) a leaf with a very heavy honeydew deposit (320 $\mu g\ cm^{-2}$); 3) a normal, green, healthy appearing leaf; and 4) a leaf with a dark, furry *Aspergillus sp.* fungus that was growing on an old honeydew residue. A constant 45° angle was maintained between the sun and the spectroradiometer; viewing angle was normal the leaf in the principal plane of the sun.

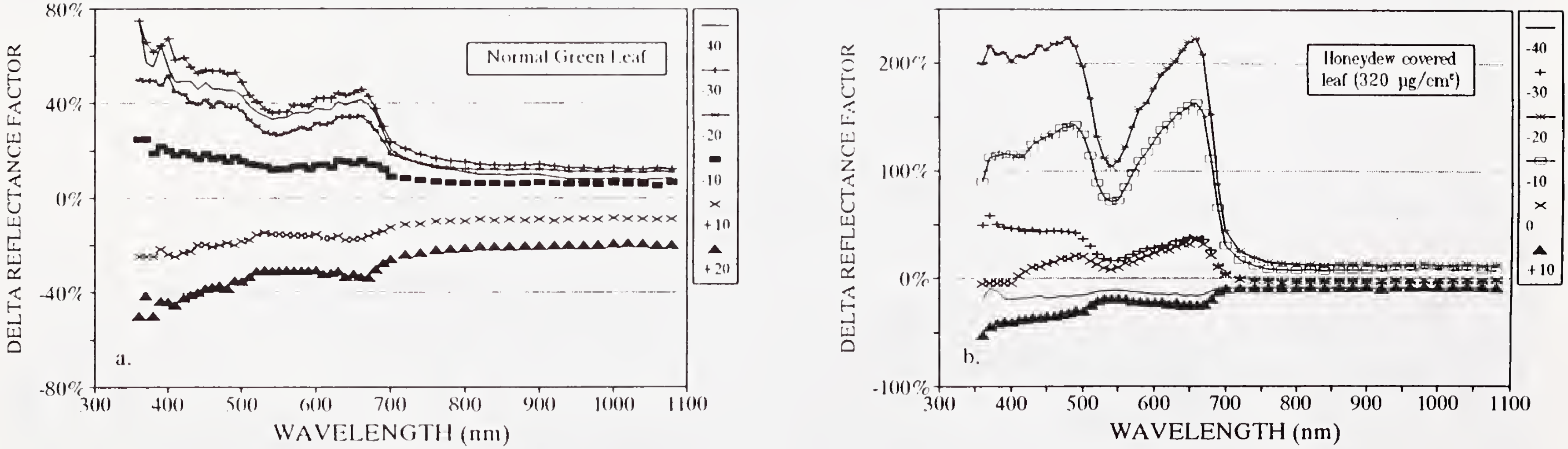

Figure 2. The percentage change in bidirectional reflectance factors (BRF) of a normal green cotton leaf as a function of viewing angle (fig. 2a). Delta BRFs for each off-nadir viewing angle were computed relative to spectral reflectances when sensor viewing angle was perpendicular to the leaf surface. Figure 2b shows the change in BRF for a honeydew covered cotton leaf as a function of leaf angle. Data for this figure were computed relative to the spectra obtained from the same leaf viewed from the same angle after the leaf had been rinsed to remove honeydew and allowed to air dry. In both parts of this figure, the angle between the spectroradiometer and the sun was maintained at 45°; view azimuth was in the principal plane of the sun.

NORMALIZATION OF SUN/VIEW ANGLE EFFECTS ON VEGETATION INDICES WITH BIDIRECTIONAL REFLECTANCE FUNCTION MODELS

J. Qi, Physical Scientist; and M.S. Moran, Physical Scientist

PROBLEM: To characterize terrestrial vegetation dynamics with remotely sensed data at regional and global scale for environmental change studies, sensors with large spatial coverage and high temporal frequency have been the major devices that provide needed data. Examples are the advanced very high resolution radiometer (AVHRR) on the national oceanic and atmospheric administration (NOAA) satellite series and the proposed moderate-resolution imaging spectrometer (MODIS) to be on board the Earth Observing System (EOS) platforms. These sensors have the ability to sense the entire earth on a daily basis because of their large field of view (FOV). Vegetation indices computed with these data sets, however, are dependent on the sensor's viewing geometry and the sun's position (Huete et al., 1992, and Qi et al., 1994). Variation in vegetation index values due to sensor's view angle difference can be much larger than that due to the vegetation itself variation. It is difficult, therefore, to use vegetation indices to monitor vegetation changes with remote sensing data provided by these large FOV sensors, and only qualitative estimation of vegetation with remote sensing data is possible if the bidirectional effect is not resolved. To utilize efficiently the data acquired by these sensors, the bidirectional effect on vegetation indices must be resolved. Our objective is, therefore, to normalize sensor's view angle effects on vegetation indices computation so that quantitative estimation of surface vegetation parameters would be possible.

APPROACH: Spectral albedo is an invariant variable with respect to the sensor's viewing geometry, since it is defined as the hemispherical reflectance of the surface within the specific spectral waveband. Our approach to view-angle normalization was, therefore, to compute vegetation indices with spectral albedos instead of spectral reflectances. To compute spectral albedos, we used existing bidirectional reflectance distribution function (BRDF) models and a limited number of spectral reflectance measurements. These models were first inverted with the measured reflectances, and then spectral albedos are integrated. Since most BRDF models are fairly accurate, we selected the model by Rahman et al. (1993 a and b), for this work. This model is semiempirical, and only three parameters are required for the inversion. The spectral reflectance data were acquired with ASAS sensor and Exotech radiometer (with equivalent SPOT XS filters) mounted on two aircraft flown at 5000 and 150 meters, respectively, above ground over alfalfa, cotton, and pecan canopies at the University of Arizona Maricopa Agricultural Center near Phoenix, Arizona. Both ASAS and Exotech data were acquired at seven different view angles at different times of the day to encompass view angle variations as well as solar position changes. These two data sets were described by Moran et al. (1991).

FINDINGS: As per definition, the view angle effect disappeared in the spectral albedos (fig. 1). However, the spectral albedos were still influenced by the solar position because of the fact that the solar position directly affect the proportion of the shadows seen by the sensors. The general trends of these spectral albedos in all spectral bands (green: XS1; red: XS2; and NIR: XS3) increased with solar zenith angles for alfalfa, cotton, and pecan sites, with exception of the soil site where the albedos of all three spectral bands slightly decreased at large solar zenith angles. Apparently, the spectral albedos were invariant with view angles, by definition, while the spectral reflectances were dependent on not only the position of the sun but also the position of the remote sensor. The normalized difference vegetation index (NDVI) values calculated with spectral albedos of the ASAS data were compared with those values calculated with reflectances in figure 2 as a function of the solar zenith angles. The solid lines were the NDVI values computed with data collected on September 7, 1991, while the dashed lines were those computed from September 8 data. The stars (*) were the NDVI values calculated with spectral reflectances of September 7, and the crosses (+) were those of September 8. The vertical variations of those data points were due to the sensor view angle changes, while horizontal variations were due to the solar zenith angles.

The view angle effects seen with reflectance-based NDVI disappeared in the albedo-based NDVI. The variation of the reflectance-based NDVI due to view angles was 17%, 20%, 20%, and 10% for alfalfa, soil, pecan, and cotton sites, respectively, while the variation due to the solar zenith angle differences was 12%, 25%, 15%, and 5% for these four targets studied. In comparison, the variation in spectral albedo-based NDVI due to solar position difference was 8%, 11%, 6%, and 2% for alfalfa, soil, pecan, and cotton sites, respectively.

INTERPRETATION: Spectral albedos are invariant variables with respect to the sensor view angles that can be derived from multidirectional spectral reflectance measurements and BRDF models. When the albedos were used in vegetation index calculations, the view angle effects were eliminated, and the sun angle effect was minimized. This would improve the accuracy in estimation of vegetation properties with remote sensing data. Although promising, the albedo-based vegetation indices may not be suitable for large images since substantial inversion and simulation time is needed. This problem can be addressed by employing simple BRDF models or by using advanced image processing techniques, which needs to be investigated. The albedo-based vegetation index could be dependent upon the performance of the selected BRDF models since the albedo calculation was achieved with simulated data. Consequently, the selection or development of a simple, but accurate, model might be crucial. Nevertheless, the albedo-based vegetation indices were void of the view angle effects and only minimally affected by solar position, whereas the reflectance-based indices are strongly dependent on both sensor and solar positions. This spectral albedo approach would certainly improve the information extraction about crops with remotely sensed data by reducing possible external noise related to sun/view angle effects.

FUTURE PLANS: The next step in this approach is to test the sensitivity of the spectral albedos to the selection of different BRDF models and adapt this approach to an operational procedure in practical application.

COOPERATORS: Francois Cabot and Gerard Dedieu, LERTS, Toulouse, France.

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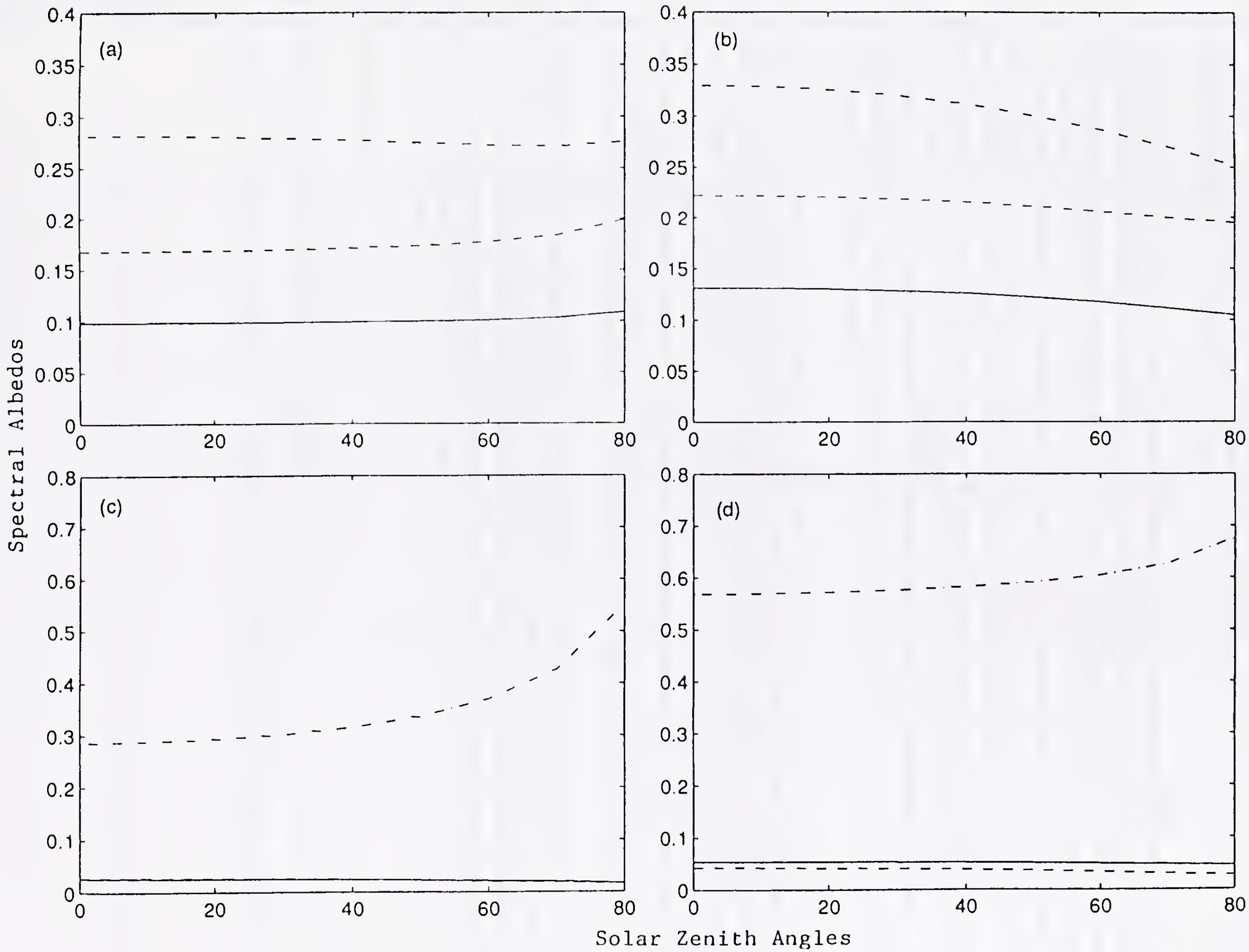

Figure 1. Spectral albedos calculated with simulated bidirectional reflectances for alfalfa (a), soil (b), pecan (c), and cotton (d) study sites using ASAS data. The solid lines are XS1, dashed line are XS2, and the dotted lines are the XS3 bands.

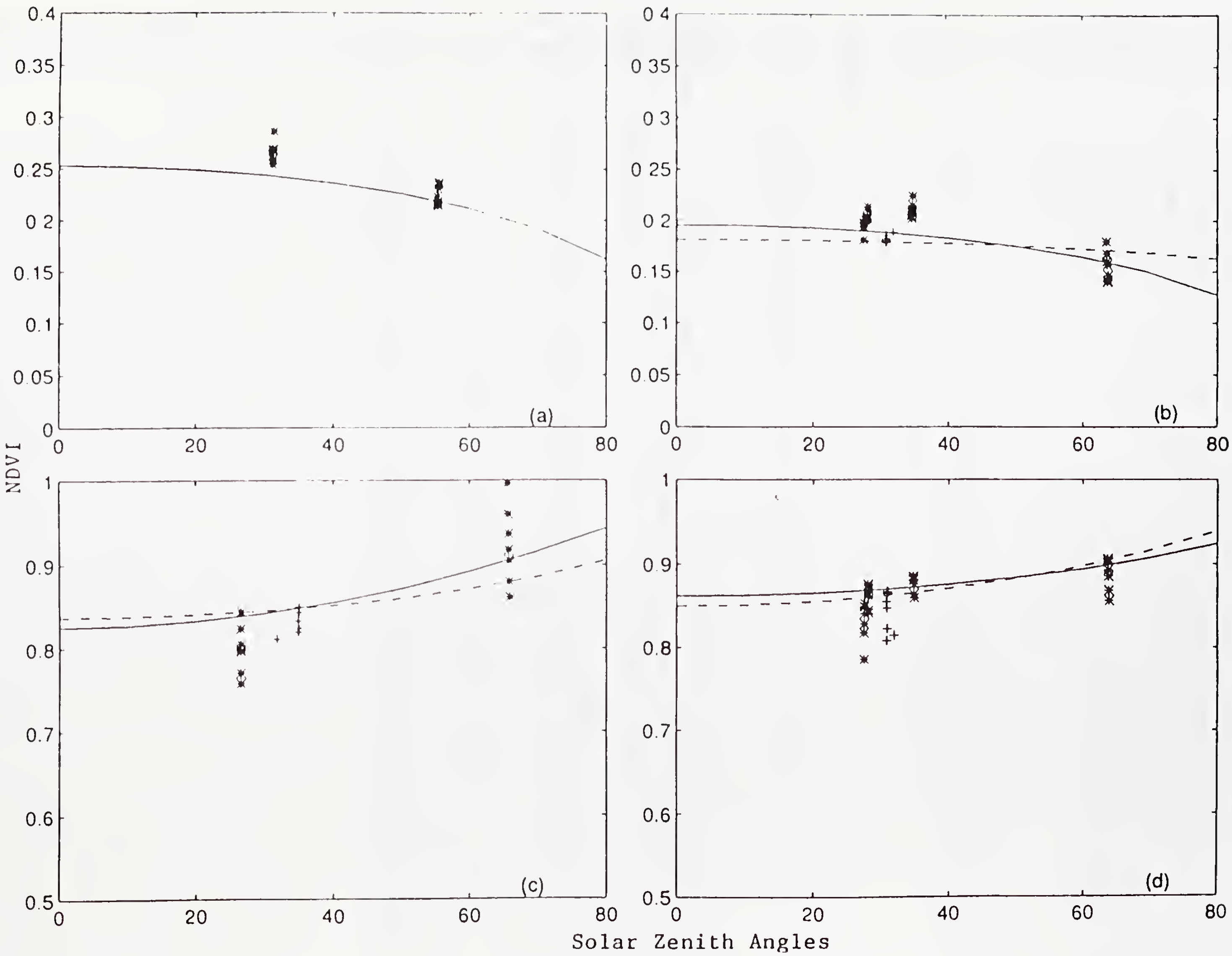

Figure 2. The NDVI values of alfalfa (a), soil (b), pecan (c), and cotton (d) study sites computed with albedos (lines). The stars (*) and crosses (+) are the NDVI values calculated with spectral reflectances.

FIELD TESTING SPECTROMETER ACCURACY USING FRAUNHOFER LINES

T.R. Clarke, Physical Scientist and P.J. Pinter, Jr., Research Biologist

PROBLEM: The advent of light weight, high resolution portable spectrometers has reduced the once herculean task of making field spectral measurements of plant canopies to a very manageable routine. The spectral accuracy of such devices is critical to the usefulness of the data being collected, and this accuracy has been verifiable only during infrequent factory recalibrations. A method of testing instrument accuracy for each user session is necessary to insure the integrity of the information collected.

APPROACH: A barium sulfate-coated reflectance standard is typically employed in field measurements to measure incident irradiance for reflectance computations. These reference panel measurements can also be used as a check of spectral accuracy, using the Fraunhofer absorption lines of impinging solar radiation. Most of these absorption features are extremely narrow and are the result of selective absorption of light by elemental gases in either the sun's or the earth's atmosphere, the latter being termed telluric absorption lines. The major Fraunhofer lines in the visible and near infrared spectrum are given in table 1. Lines b1 through b4 are very close together and would appear as a single absorption feature to instruments with resolutions coarser than 1 nanometer.

Spectral measurements of a $BaSO_4$ panel were made using a Personal Spectrometer II (Analytical Spectral Devices, Inc., serial number 1222), which had a factory specified spectral resolution of approximately 1.4nm. All absorption features listed in table 1 were discernable in the resulting spectrograph, as illustrated in figure 1. A scan of a barium sulfate surface illuminated by incandescent light showed that these particular features were not artifacts of the instrument or the surface material.

FINDINGS: A comparison of the instrument's response minima is given with the corresponding Fraunhofer lines in table 2. The difference between measured and actual minima in each case was less than the instrument's spectral resolution in the visible wavelengths, with a slight overestimate of wavelength in the near infrared.

Several minor absorption features were apparent in the PS II spectrograph that did not correspond to major Fraunhofer lines. The D and E lines were not as readily discernable as the other major Fraunhofer lines and could be confused with these minor features. It is therefore recommended that the A, B, C, b1-b4, F and G lines be used to check the instrument's accuracy. The calcium absorption lines at 854.2 nm and 866.2 nm were barely discernable in the PS II spectrograph (fig. 2), but provide the only check of longer wavelengths.

INTERPRETATION: Cataloging detailed reflectance spectra of plant canopies throughout the growing season may prove useful in determining crop type and growth stage remotely, perhaps leading to the development of radiometers specifically designed to adjust computer growth models used to estimate evapotranspiration and schedule irrigations. Remote sensing instruments could also be developed to detect certain kinds of stress using these spectra as a guide. Now that a nearly automatic check of spectrometer accuracy has been developed, the spectral measurements can be used with confidence.

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Table 1. Major Fraunhofer lines of the visible and near infrared spectrum (from the Handbook of Chemistry and Physics, 55th Edition, and Kurucz et al. 1984).

Line designation	Wavelength (nm)	Element	Origin
(none)	866.2	Calcium	Solar
(none)	854.2	Calcium	Solar
A	760.0	Oxygen	Telluric
B	687.0	Oxygen	Telluric
C	656.3	α Hydrogen	Solar
D	589.0 & 589.6	Sodium	Solar
E	527.0	Iron	Solar
b1 - b4	516.7, 516.8, 517.3, & 518.4	Magnesium & Iron	Solar
F	486.1	ß Hydrogen	Solar
G	430.8	Iron & Calcium	Solar

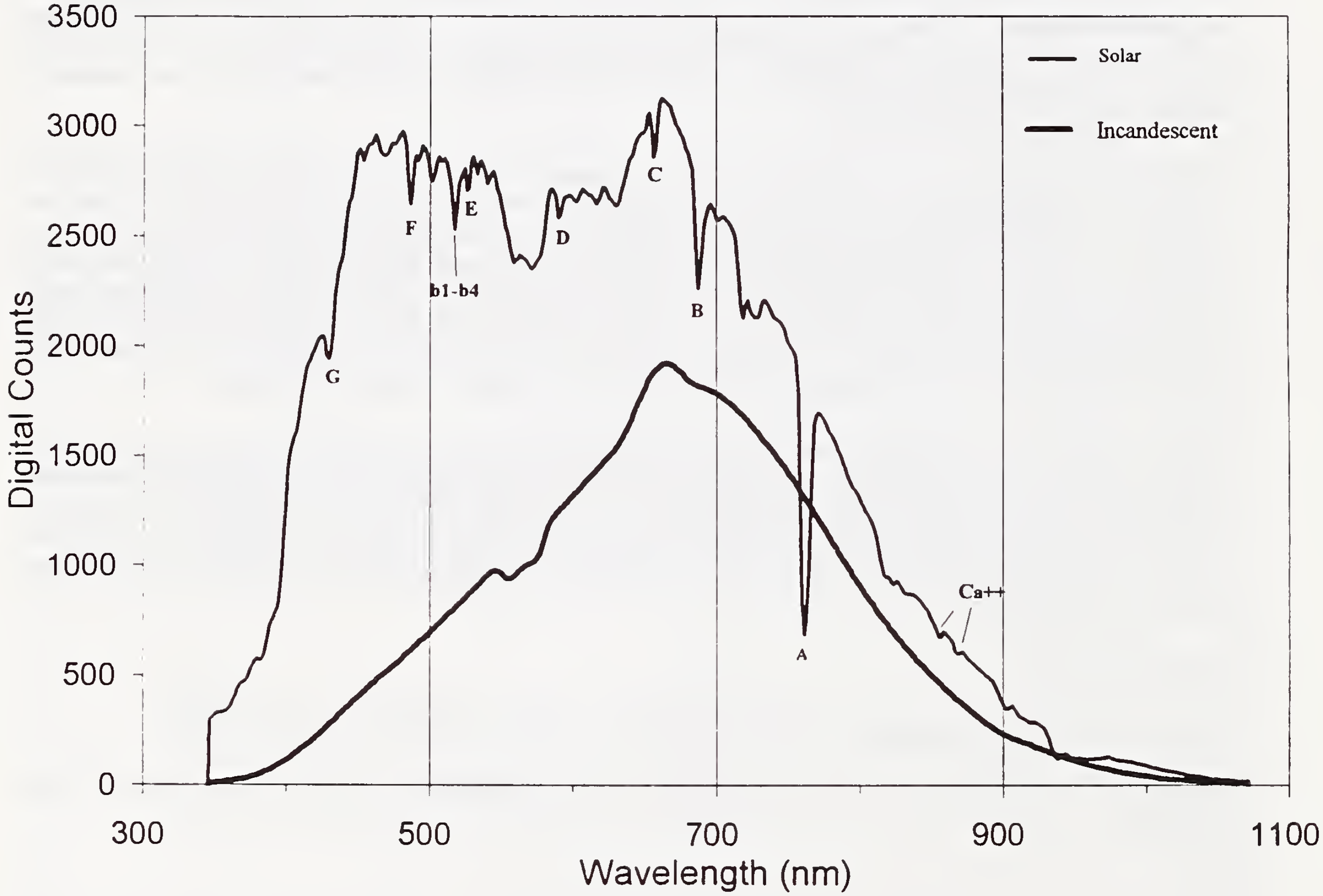


Figure 1. PS II spectra of a barium sulfate surface illuminated by sunlight and an incandescent light source. Fraunhofer lines as described in table 1 are shown in the solar illuminated surface spectrum and lacking in the artificially illuminated surface spectrum. The depression between 550 nm and 580 nm is assumed to be an artifact of the measuring device.

Table 2. Comparison of spectrograph minima of a barium sulfate panel as measured by a PS II portable spectrometer (computed using factory-supplied calibration) to the major Fraunhofer lines. The instrument's spectral resolution is 1.42 nanometers.

PS-II (nm)	Fraunhofer (nm)	Difference (nm)	Error in PSII Bandwidths
429.8	430.8	-1.0	<1
486.6	486.1	+0.5	<1
517.8	517.5(avg)	+0.3	<1
657.0	656.3	+0.7	<1
688.2	687.0	+1.2	<1
762.0	760.0	+2.0	1
855.8	854.2	+1.6	1
868.5	866.2	+2.3	1

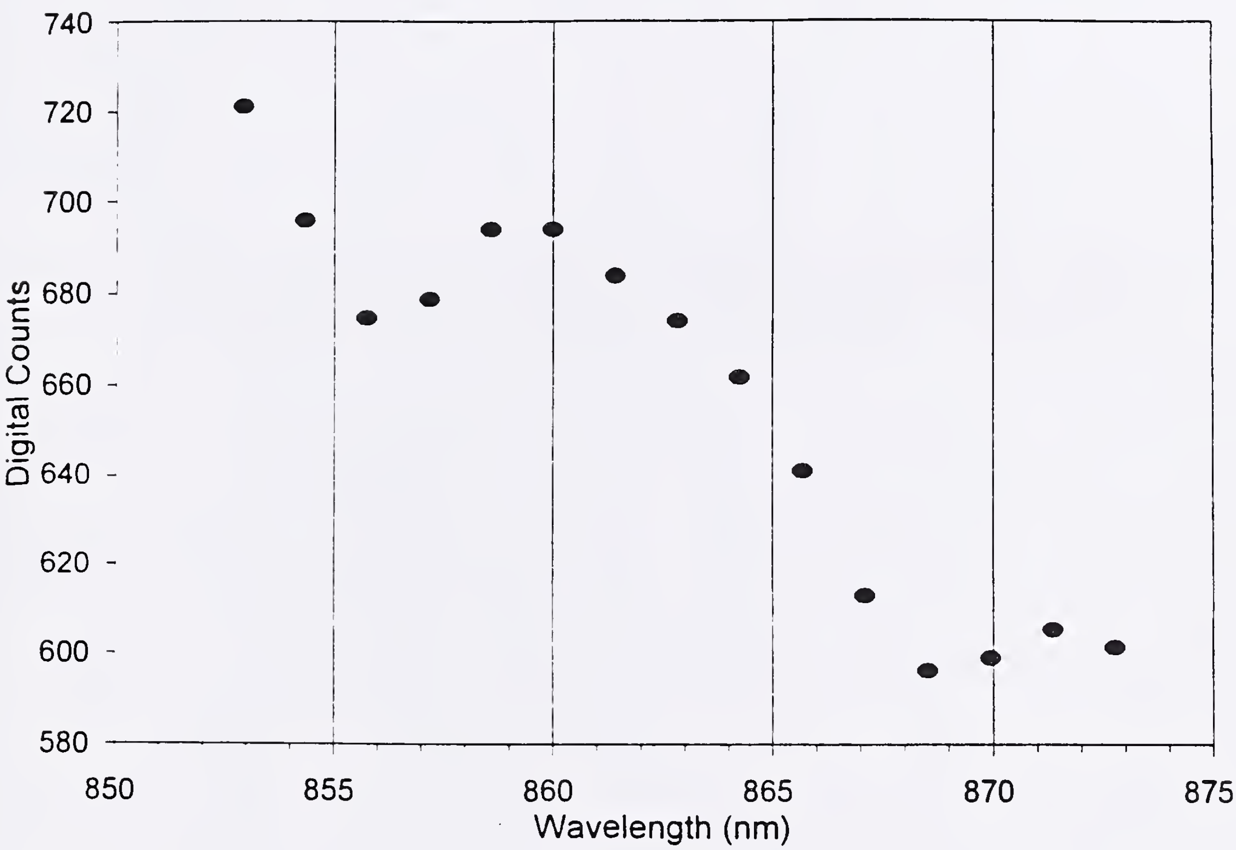


Figure 2. Enlarged detail of the PS II solar-illuminated panel spectrum, showing Ca^{++} absorption features at approximately 855.8 and 868.5 nanometers. These absorption features actually exist at 854.2 and 866.2 nanometers, respectively, indicating a slight error in instrument accuracy.

AUTOMATED FARM MANAGEMENT USING REMOTE SENSING AND EXPERT SYSTEMS

REFLECTANCE FACTOR RETRIEVAL FROM LANDSAT TM AND SPOT HRV DATA FOR BRIGHT AND DARK TARGETS

M.S. Moran, T.R. Clarke, and J. Qi; Physical Scientist

PROBLEM: Spectral images from satellite-based sensors have long been promoted for earth-monitoring applications such as land-cover change detection and evaluation of global energy balance. Such land-surface studies are often based on reflectance values retrieved from the Landsat Thematic Mapper (TM) and SPOT High Resolution Visible (HRV) sensors. Retrieval of reflectance values from satellite sensor digital count requires knowledge of the atmospheric conditions and the sensor absolute calibration. In most cases, atmospheric conditions are simulated with a radiative transfer code, and sensor calibration coefficients are obtained from pre-flight sensor calibrations or in-flight calibrations over bright surfaces (such as White Sands, New Mexico, USA, or La Crau, France). Though these procedures are well-accepted, there have been few studies specifically designed to validate the accuracy of such reflectance factor retrievals (RFR) for both bright and dark targets.

APPROACH: Data from two experiments conducted at the Maricopa Agricultural Center (MAC) south of Phoenix, Arizona, were analyzed to quantify the accuracy of RFR from the Landsat TM and SPOT HRV sensors. In one, we obtained two HRV scenes on two consecutive days (+10° and -23° viewing angle) with simultaneous measurements of reflectance in the same viewing and azimuth angles using ground-based and low-altitude airborne instruments:

Date	Platform	Sensor	Time	Θ_v	Weather
7 Sep	SPOT2	HRV1	11:34	+25	Cloudfree
8 Sep	SPOT2	HRV1	11:14	-09	Cloudfree
7 Sep	C-130	ASAS	11:30	Multi	Cloudfree
8 Sep	C-130	ASAS	11:15	Multi	Cloudfree

In another experiment, we obtained a TM and HRV scene on a single day with both sensors viewing near-nadir (±5°) and simultaneous measurements of ground reflectance with nadir-looking sensors:

Platform	Sensor	Time	Θ_v	Weather
SPOT2	HRV1	11:24	3.3	Cloudfree
Landsat5	TM	10:26	5.4	Cloudfree
Cessna	Exotech	10:26 11:24	0.0	Cloudfree

For both experiments, measurements of atmospheric conditions were made during each overpass. Other data included measurements made with yoke-based and aircraft-based 4-band radiometers and the NASA Advanced Solid-State Array Spectrometer (ASAS) aboard a C130 aircraft.

FINDINGS: Reflectance factors retrieved from the C130-based ASAS sensor compared well with those measured with yoke-based instruments at ground level (fig. 1). Results showed that the RFR from the TM and HRV sensors generally resulted in an overestimation of dark target reflectance (up to 0.05 reflectance in the visible), and an underestimation of bright target reflectance (up to 0.1 reflectance in the near-infrared) (fig. 2). Even greater error was possible when RFR was based on out-dated sensor calibrations, particularly those conducted pre-launch. There was supporting evidence from studies at three sites (White Sands, New Mexico; Maricopa, Arizona; and Walnut Gulch, Arizona) that the Landsat5 TM sensor sensitivity may have degraded by as much as 20% from the pre-launch calibration.

Based on the varying success with RFR from the ASAS, HRV, and TM sensors, it was reasonable to focus our attention on effects of atmospheric correction and sensor calibration. This was accomplished using the TM and HRV data acquired when both sensors had similar viewing geometry on the same day for the same targets. We inverted the reflectance retrieval process and backed out the calibration coefficients that would be necessary to result in near-zero error in RFR (fig. 3). For the TM sensor, the following calibration equations would result.

$$\text{TM1: } L_i = (DC\text{-}49.9)1.17;\ \text{TM2: } L_i = (DC\text{-}16.3)1.85;$$
$$\text{TM3: } L_i = (DC\text{-}15.5)1.38;\ \text{and TM4: } L_i = (DC\text{-}9.1)1.13, \tag{1}$$

where L_i is in units of W m^{-2} sr^{-1} μm^{-1}. For the HRV sensor, the calibration equations would be

$$\text{XS1: } L_i = (DC\text{-}8.85)2.88;\ \text{XS2: } L_i = (DC\text{-}8.64)3.53;\ \text{and XS3: } L_i = (DC\text{-}14.2)1.78, \tag{2}$$

where HRV DC has been corrected to a gain of 3 for comparison with previously-published calibration coefficients. These offsets are orders of magnitude larger than the offsets published for the pre-launch calibration. Thus, it is safe to conclude that the error in RFR was not associated solely with the sensor calibration. The error was more likely a sum of errors associated with calibration and atmospheric correction.

INTERPRETATION: This work demonstrates the potential of using sensors from several satellites for such applications as farm administration, land change detection, and natural resource management. The advantage of using two or more sensors is an increase in the frequency of coverage; the disadvantage is the danger of mistaking changes in sensitivity of the sensor with changes in ground parameters such as vegetation cover. Our results suggest that with proper sensor calibration and atmospheric correction of the sensor output, it is possible to combine images from multiple sensors for a single application. These results could encourage the conversion of existing satellite sensors from military to civilian applications.

FUTURE PLANS: Future work on this issue should address a rigorous test of the accuracy of RTMs for atmospheric correction of satellite sensor data. Such a test could be conducted for targets of varying reflectance ranging from 0.0 to 0.6 for a single sensor spectral band. This would minimize uncertainties due to band-to-band biases that were present in the agricultural targets used in these studies. Another approach would be to look at very dark surface targets (e.g., ocean) at night to confirm or disprove the large offset values presented in figure 3.

COOPERATORS: F. Cabot, LERTS, Toulouse, France; K.J. Thome, Univ. of Ariz. Optical Science Center, Tucson, Arizona.

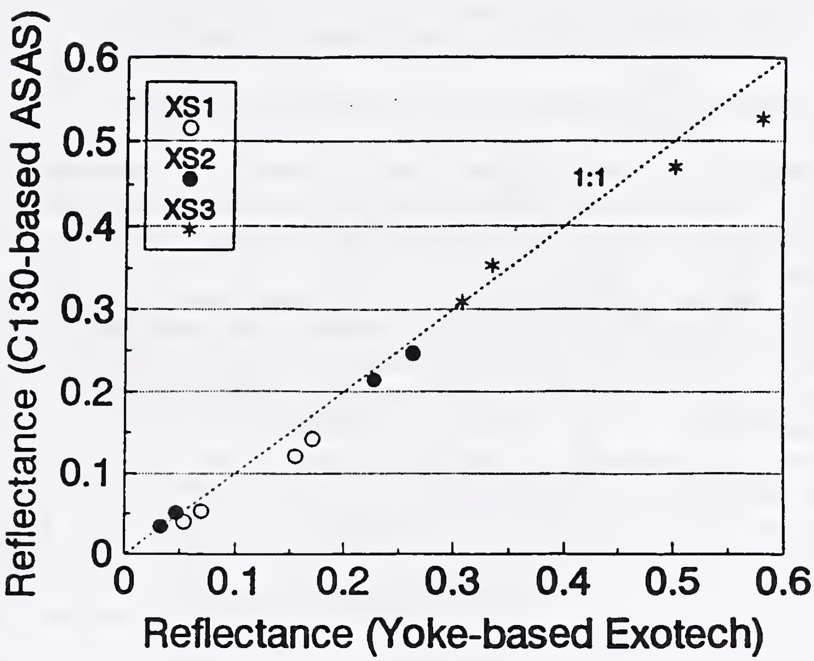
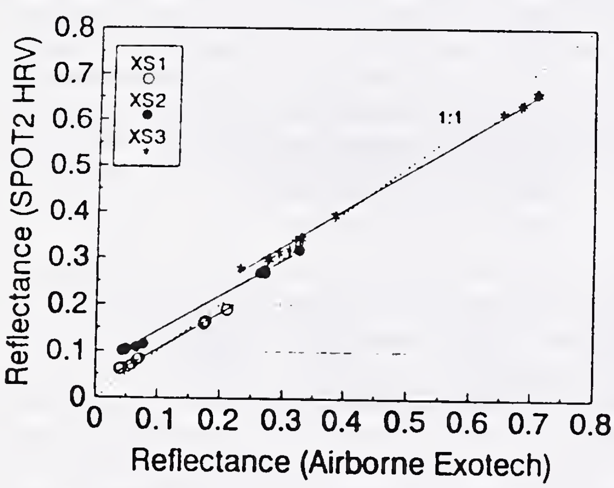


Figure 1. Comparison of reflectances retrieved from ASAS digital counts (integrated over the spectral response of the HRV sensor) with yoke-based measurements with sensors in the same orientation as the HRV sensors. The 12 data points are measurements from 2 days, 2 targets (bare soil and vegetation), and 3 spectral bands (HRV XS1-XS3).



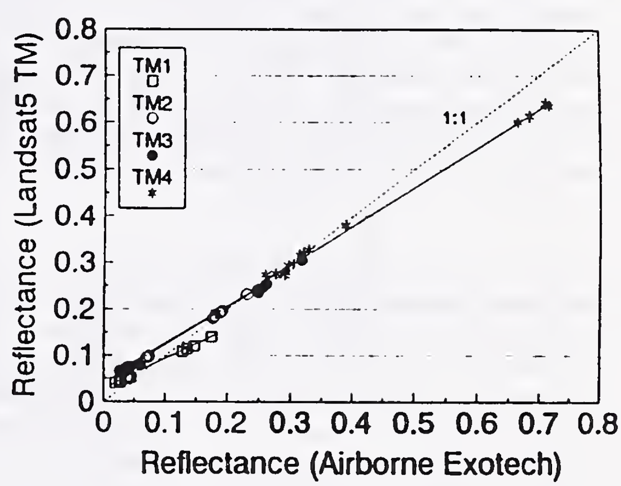
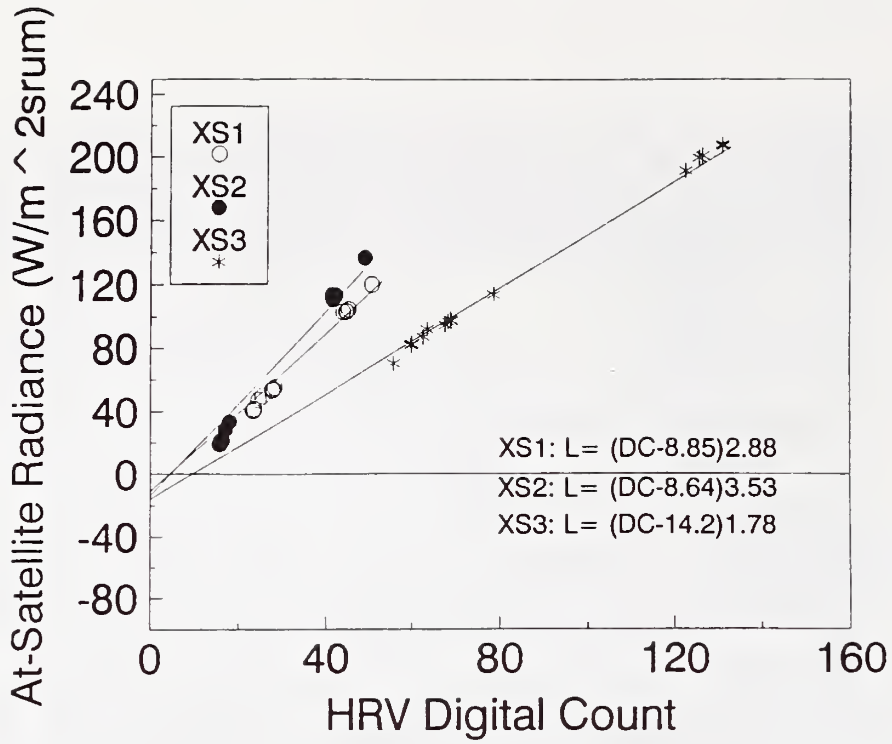


Figure 2. Comparison of reflectances retrieved from SPOT HRV and Landsat TM digital counts with aircraft-based Exotech measurements with both sensors in a nadir-viewing configuration. The data points represent measurements from several targets within fields of bare soil, cotton, and pecan trees.



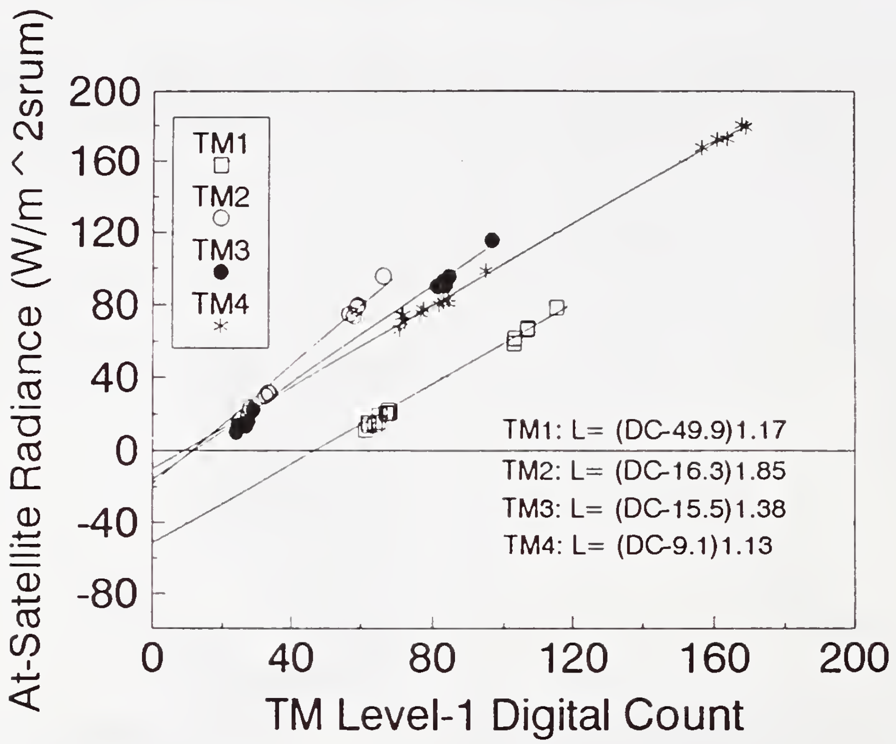


Figure 3. SPOT HRV and Landsat-TM calibration coefficients back-calculated from the measurements made at MAC during the Mini-MAC'92 Experiment. The data points represent measurements from several targets within fields of bare soil, cotton, and pecan trees.

BIOPHYSICAL PARAMETER RETRIEVALS USING MULTIDIRECTIONAL MEASUREMENTS

J. Qi, Physical Scientist; and M.S. Moran, Physical Scientist

PROBLEM: Spectral reflectance measurements made at varying view angles can be substantially different because of the bidirectional reflectance properties of land surface (Deering, 1989; Jackson et al., 1990; and Qi et al., 1994). It is difficult or impossible to compare quantitatively data collected with sensors of different geometric configurations. Much effort has been devoted to the normalization of bidirectional effects by developing bidirectional reflectance distribution function (BRDF) models. In the past ten years, more than a dozen BRDF models have been developed. Some of them are empirical and some are physical based. These models can be used to predict the bidirectional properties when given enough input information, and can be potentially inverted to infer surface physical properties of the surface. Empirical models are easier to be inverted than physical models, but information obtained by inversion of these models are limited. The retrieved information from inversions of physical models, on the other hand, is more meaningful, but difficult to invert since these models require simultaneous multidirectional measurements. From a practical point of view, this is not possible not only because of the generic design of remote sensing systems, but also for economic reasons. Consequently, inversion of these BRDF models for surface information extraction on an operational basis needs to be investigated. The objective of this study was to develop a practically operational algorithm that utilizes BRDF models to retrieve surface physical or biophysical parameters.

APPROACH: Since physical BRDF models contain meaningful information about surface while empirical models are easier to invert, we combined these two types of BRDF models to retrieve vegetation parameters with a limited number of multidirectional measurements. The strategy is illustrated in figure 1. First, with a limited number (N) of multidirectional reflectance measurements, a simple empirical (A) was inverted to obtain a set of parameters required by the model itself. Then, these retrieved parameters were used in the direct simulation with the same model to generate a large data set of multidirectional reflectances (BRDF). The generated data were further used in the inversion of a physically based model (B), from which some parameters characterizing vegetation properties could be retrieved. In this study, we attempted to retrieve leaf reflectance and transmittance using model B. Finally, leaf reflectance and transmittance were used with other inputs in a third BRDF model (C) to retrieve lead area index (LAI). In this study, a simple BRDF model by Rahman et al.(1993), which requires only three input parameters (one mean-level of reflectance and two anisotropy factors) was selected in the first step, and a second model by Verstraete et al. (1990), which requires seven input parameters (average single scattering albedo, asymmetry factor, leaf orientation, interception cross section of the canopy, Henyey-Greenstein function, and parameter depending on leaf orientation), was chosen for the second step to retrieve leaf transmittance and leaf reflectance. Finally the SAIL model (Verhoef, 1984), which requires four input parameters (soil reflectance, leaf reflectance and transmittance, and leaf area index), was selected for the final step in which LAI values were retrieved.

FINDINGS: This algorithm was tested with two data sets. The first data set was the ASAS data over alfalfa, cotton, and pecan tree canopies; and the second data set consisted of multitemporal radiometric measurements over a growing wheat canopy. The results with the first data set were shown in figure 1 for alfalfa, cotton, and pecan tree canopies. The retrieved leaf area index (LAI) values for the three canopies matched reasonably well with the measurements, considering the fact that the measurement uncertainties (the vertical AB bar in figure 1) was quite large. The retrieved LAI values with the data of two consecutive days (day-of-year 250 and 251) also agreed well. This suggested that the algorithm is valid for LAI retrieval with multidirectional measurements. The algorithm was further applied to the multitemporal wheat reflectance data. As wheat data set was obtained with a nadir view angle (but different sun angles), we used ten measurements during the peak growing season from day-of-year (DOY) 90 to 100 in the first step to obtain leaf reflectance and transmittance, which was assumed to be constant throughout the whole growing season. The results were plotted in figure 3 as a function of DOY. The circles were the retrieved LAI, while the solid line was the measurements. Seasonal LAI variations were predicted fairly accurately with the algorithm, indicating that the algorithm can be used not only with multidirectional, but also multitemporal radiometric measurements.

INTERPRETATION: This algorithm combined several existing BRDF models in surface parameter retrievals, such as the vegetation optical properties and density. The results, however, may vary depending on the model selection. Most existing models proved to be fairly accurate in BRDF prediction. Consequently, the retrieved surface parameters should be reasonably accurate. The potential application of this algorithm is the mapping of vegetation densities and crop types, and crops growth monitoring on an operational basis with multitemporal remote sensing measurements. One of the advantages of this algorithm is that it voids the bidirectional effects as suffered by currently used vegetation indices. Another advantage of this algorithm is the multiparameter retrievals with remote sensing measurements, such as the retrieval of both vegetation optical properties and densities in this study.

FUTURE PLANS: This algorithm will be further tested with satellite measurements to investigate the possible application of this algorithm to a large spatial scale as well as the investigation of how the atmosphere would influence the accuracy of surface parameter estimations.

COOPERATORS: Francois Cabot and Gerard Dedieu, LERTS, Toulouse, France.

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Verstraete M. M., B. Pinty, and R. E. Dickinson, 1990, A physical model of the bidirectional reflectance of vegetation canopies, 1: Theory, J. Geophys. Res. 95:11755-11765.

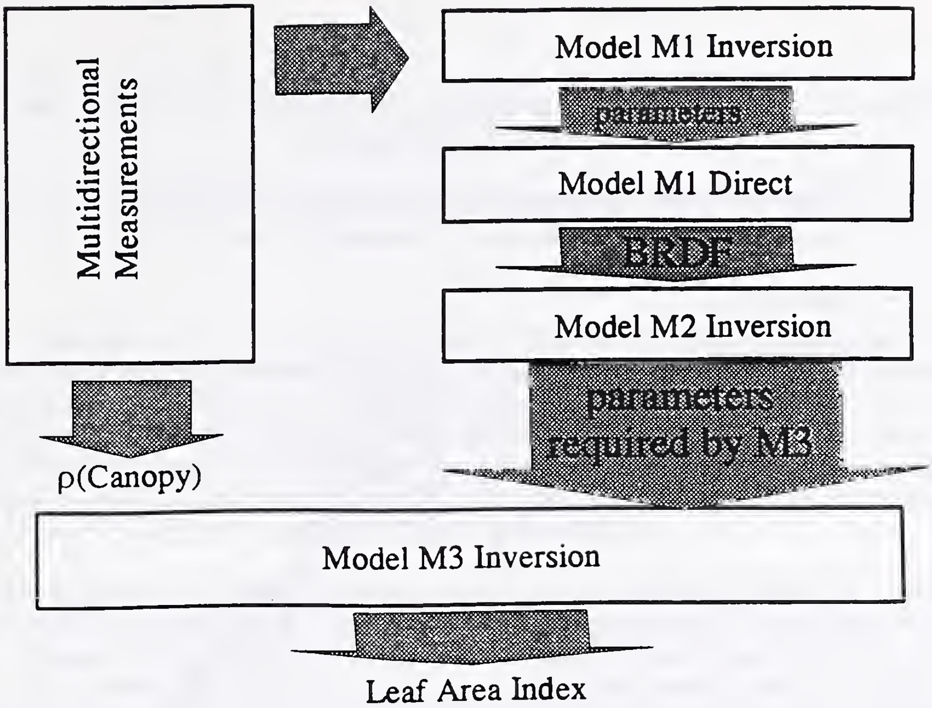

Figure 1. A model-to-model flow chart that combines several BRDF models for surface parameter estimations.

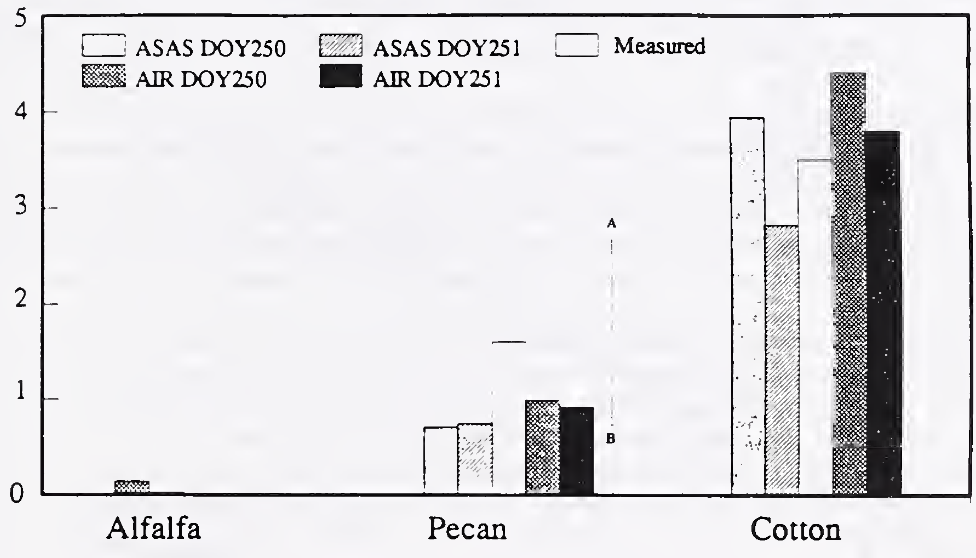

Figure 2. Retrieved leaf area index values with ASAS and aircraft data for the three canopy types (alfalfa, cotton, and pecan trees).

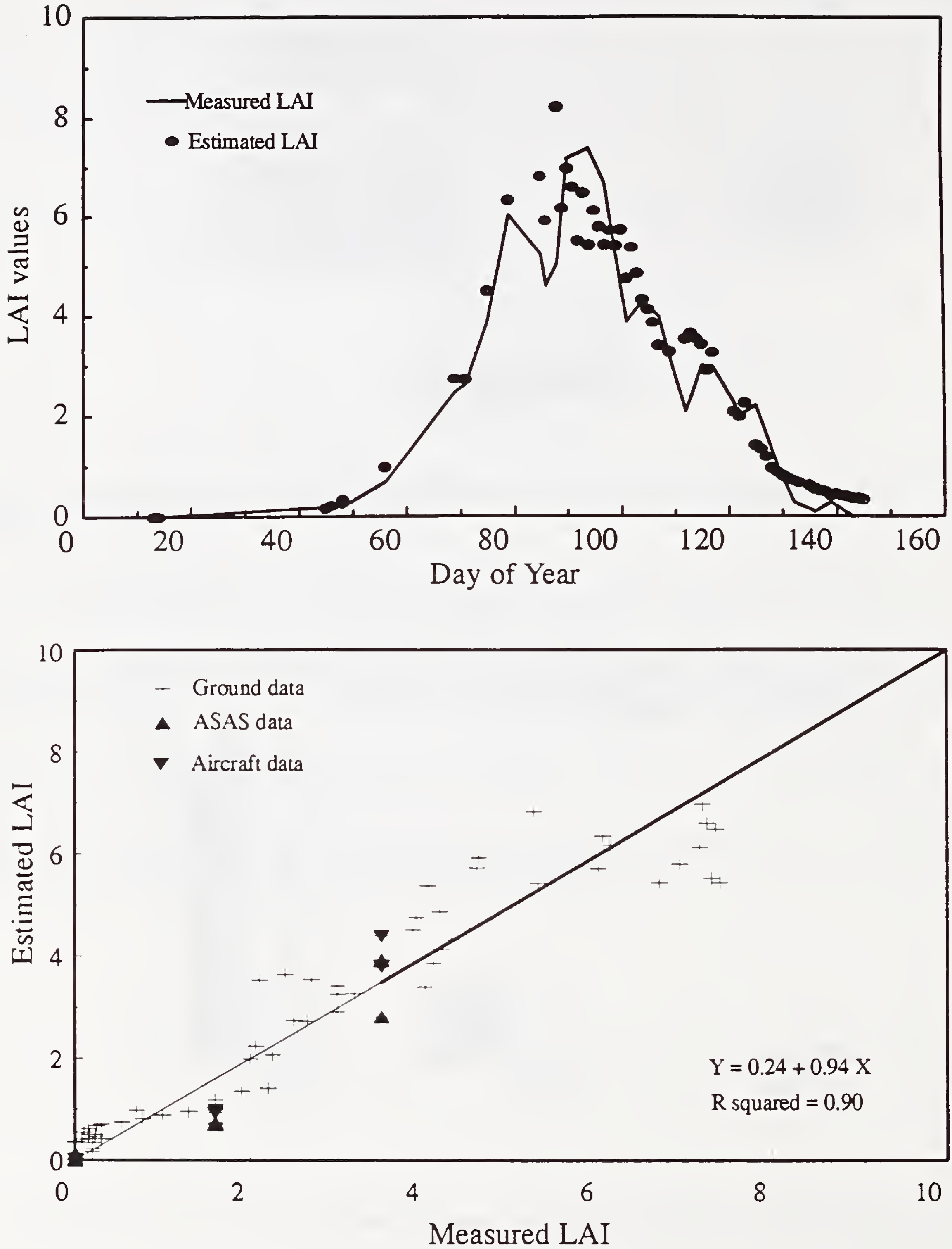

Figure 3. Retrieved leaf area index values with multitemporal ground measurements over a growing wheat canopy: (a) Temporal LAI variation, (b) Comparison.

HIGH RESOLUTION MULTITEMPORAL AIRBORNE IMAGERY TO TEST REMOTE SENSING AS A FARM MANAGEMENT TOOL

T.R. Clarke, Physical Scientist; M.S. Moran, Physical Scientist;
P.J. Pinter, Jr., Research Biologist; and J. Qi, Physical Scientist

PROBLEM: The use of airborne multispectral imagery as an aid to farm management, particularly to assist in irrigation scheduling, has been suggested for over a decade. The recent development of commercially available thermal scanners and optical digital cameras, as well as computers able to handle the large data sets created by these sensors, has brought this hypothetical concept to the threshold of practicality. However, a season-long set of high resolution multispectral images, along with detailed supporting ground data, has not been available to researchers for evaluating the usefulness of such information. This led to implementation of the Multispectral Airborne Demonstration over the Maricopa Agricultural Center, or MADMAC.

APPROACH: Efforts were coordinated between scientists at three locations. Engineers at Utah State University's Department of Biological and Irrigation Engineering provided the airborne remote sensing platform and initial image processing. Managers of The University of Arizona Maricopa Agricultural Center (MAC) provided their expertise and access to the 770 hectare research and demonstration farm located south of Phoenix, Arizona. Personnel from the U.S. Water Conservation Laboratory collected a variety of ground measurements on the fifteen overflight days, which spanned the cotton growing season from April 12 to September 28, 1994. Table 1 offers a brief summary of the flights attempted and made. Flights were scheduled to occur just prior to solar noon, thereby avoiding afternoon clouds and mid-day instrument shadow problems.

The Utah State University airborne platform consisted of three optical video cameras with green (0.545-0.555 μm), red (0.645-0.655μm), and near infrared (0.840-0.860μm) filters, a thermal scanning video filtered to 8.0-12.0μm, a 4-band visible and near infrared radiometer, and a thermal infrared radiometer. The aircraft flew over the entire farm at 2,300 meters above the surface, providing a ground resolution of approximately 2 meters in the optical bands and 4 meters in the thermal band. The data set for each overflight consisted of over 40 overlapping images per band. The aircraft then dropped to a lower altitude and covered the research portion of the farm at a ground resolution of about 2 meters in the thermal band.

Managers of the Maricopa Agricultural Center provided full access to the demonstration farm, as well as to records of management practices such as irrigation dates and amounts, chemical applications, and cultivation. Major crops during the experiment were wheat, barley, upland and pima cotton, alfalfa, sorghum, and sudan grass. Smaller plots of oats, fruit and nut trees, safflower, bermuda grass, corn, melons, strawberries, tomatoes, jojoba, guayule, lesquerella, vernonia, and agave were also present. Several experiments involving irrigation scheduling and fertilizer application methods were being performed on cotton by University of Arizona scientists during the season.

U.S. Water Conservation Laboratory personnel performed several "ground truth" measurements on overflight days, including measurements of reflectance and temperature of large target areas, emissivity, component temperature and reflectance during partial canopy periods, solar radiation, wind speed, air temperature and humidity, biomass and leaf area index, spectrometer and light interception, and atmospheric optical depth. A detailed visual survey of the entire farm was performed on each overflight day, recording 875 separate observations of crop type, estimated plant height, growth stage and percent cover, soil surface texture and dampness, and presence of insect damage or other anomalies. A cross-calibration of aircraft and ground-based radiometers was performed prior to each flight.

FINDINGS: Mosaicking of overlapping images and their subsequent registration to a digital map of the farm is still being performed. Radiometric correction of the images has not commenced, and images cannot as yet be evaluated. An example of the type of images expected can be seen in figure 1, which is a false color digital image (not radiometrically corrected) of MAC acquired June 14, 1994. A raster-based Geographic Information System (GIS) is being used to develop a data base containing the images, visual surveys, ground-based measurements, and cultural practice records. When this data base is complete, analysis can begin.

INTERPRETATION: It became immediately apparent that the major barrier to the effective use of remote sensing as a farm management tool is the slow turn-around time between image acquisition and availability of final products (growth rate, water stress, water consumption, etc.) for analysis. Ideally, this time lag should be no more than twenty-four hours. We expected a one-to-two-week lag at this initial stage but experienced a three-to-four-month lag resulting from difficulties in the precise mosaicking of large numbers of images. Clearly, this step must be automated before a viable product can be realized.

FUTURE PLANS: When the fifteen data sets are ready for analysis, several potential products will be tested, including a growth rate map, which subtracts a previous Vegetation Index (VI) image from a more recent one; a Water Deficit Index (WDI) map, which combines thermal and VI images to show actual to potential evapotranspiration rate; a Crop Water Stress Index (CWSI) map, which is a special application of the WDI concept for scheduling irrigations; and a hypothetical Vegetation Index, Green/Red (VIGR) two-dimensional index for the detection of nutrient stress. The images will also be used to evaluate an evapotranspiration/crop model developed by Steve Maas of the U.S. Cotton Research Station.

COOPERATORS: Christopher Neale and his staff in the Department of Biological and Irrigation Engineering at Utah State University; Roy Rauschkolb, Robert Roth, Pat Murphree, and MacD Hartman of The University of Arizona Maricopa Agricultural Center; and Steve Maas, ARS, U.S. Cotton Research Station, Shafter, CA.

DATE	FLIGHT #	COMMENTS
4/12/94	4	Wheat headed, Cotton just being planted.
8/02/94	2	Wheat senescing, Cotton 0-2% cover.
5/16/94		Cancelled; in-flight mechanical problems.
5/22/94		Cancelled; attempted sabotage of aircraft
5/27/94	3	Wheat being harvested; cotton about 10% cover.
9/27/94	4	Cotton about 15% cover.
6/14/94	5	ERS-1, SPOT, & Sandia Lab overflight this week. Cotton about 25% cover.
7/06/94	8	Cotton about 50% cover.
7/12/94	7	Cotton about 60% cover. Humidity higher.
7/21/94	8	Cotton being sprayed with pesticide. About 80% cover
8/02/94	9	Very hot; cotton approaching 100% cover.
8/11/94	10	Cloud cover. Only cloudy overflight day.
8/16/94	11	Started using narrow band filters in radiometers.
8/23/94	12	Some leaf perforator damage evident in cotton.
8/31/94	13	Severe pest damage in some fields.
9/08/94	14	Heavy rain 4 days prior; hail and wind damage. Too wet for ground reflectances. Cotton being defoliated.
9/27/94		Cancelled; clouds.
9/28/94	15	Cotton being harvested

Table 1. MADMAC overflight summary.

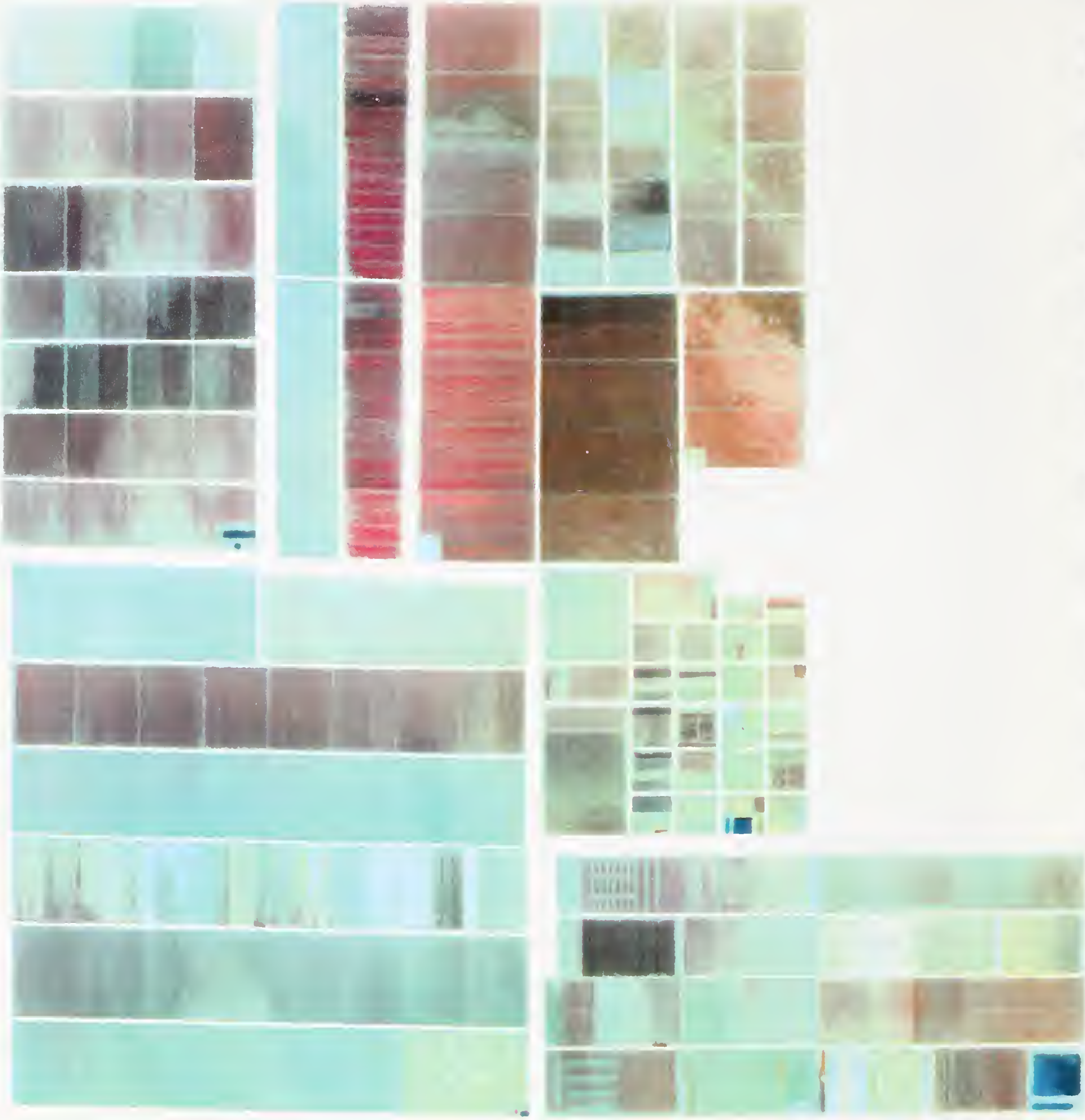

Figure 1. Multispectral digital image (near infrared, red, and green bands shown as red, green, and blue, respectively) of the Maricopa Agricultural Center on June 14, 1994. Actual image resolution is better than shown.

USING THE VIT CROP WATER STRESS INDEX TO EVALUATE SUB-SURFACE DRIP IRRIGATION SYSTEMS

T.R. Clarke, Physical Scientist; and T.A. Mitchell, Engineering Technician

PROBLEM: Water application efficiency can be greatly improved by the use of subsurface drip irrigation, but the ability to monitor soil moisture in the root zone becomes more difficult. Clogged subsurface emitters can go undetected until plant stress or damage becomes visibly evident. Furthermore, efforts to correct emitter problems by chemical flushing must be followed by a period of waiting for an obvious plant response: the plant recovers if the clog has been removed, or damage continues if the emitter remains clogged. A means of determining the efficacy of drip systems over large areas is greatly desired.

Plants receiving sufficient water through their roots have cooler leaves than those that are water stressed. Idso et al. (1981), exploited this phenomenon, developing the Crop Water Stress Index which compares canopy temperature minus air temperature to vapor pressure deficit to determine the magnitude of water stress. Hand-held infrared thermometers have been successfully used to determine water stress in individual plants and fields with complete canopies, but the exposed, hot soil found in partial canopies renders the results of such a method unusable. A concept utilizing the relationship between a radiometrically derived vegetation index and surface-minus-air temperature (VIT) was recently developed which has the potential of eliminating the effects of soil background temperature on the Crop Water Stress Index (Clarke et al., 1994). While the precise bounds and internal characteristics of this trapezoidal, two-dimensional index will not be completely understood until formal experiments are performed, practical applications have already been found in drip irrigated systems.

APPROACH: A drip irrigated melon farm located approximately 100 kilometers west of Phoenix was overflown on September 15, 1994, with a light aircraft carrying a thermal scanner (8.0-12.0μm) and two digital cameras fitted with red (0.600 - 0.670μm) and near infrared (0.780 -0.880μm) filters, at an altitude of 2,300 meters above the ground. Images were acquired of areas ranging from dry bare soil to saturated bare soil, and from nonstressed melon canopies to highly stressed post-harvest canopies.

Two of the thirty-two-hectare melon fields suffered from clogged emitters. Figure 1a is a thermal image of one field showing areas of clogged emitters as two distinct warm areas near the southern (bottom) edge. These areas appear warm because water stress damage has left more exposed soil than in the rest of the field. Treatment of the problem had begun prior to the overflight, with sulfuric acid and chlorine flushes followed by a surfactant treatment to clear calcium deposits, algae, and sediment from the drip lines.

Vegetation index (VI) images were created through a mathematical comparison of the near infrared and red images. Scatter plots comparing all VI and thermal images were analyzed, and from this nearly complete range of possible VIT points a trapezoid was empirically constructed, as seen in figure 1b. Colors were assigned to different areas of the trapezoid signifying plants that were experiencing no or little water stress (blue), mild stress (green to yellow), and severe water stress (orange and red). Areas with a wet soil surface were mapped as gray, and very low amounts of vegetative cover over dry soil were mapped as black. The Crop Water Stress (CWSI) image of the field under treatment was then produced using the above color classification scheme. These results can be seen in figure 1c.

FINDINGS: The resulting water stress map showed no water stress in the smaller clogged area and only low to mild stress in the much larger area. This would indicate that the flush treatments were almost completely effective in the smaller area and substantially improved water delivery in the larger area. Subsequent observation showed good recovery of plants in both areas. Also of interest were the small orange patches in the upper left portion of the CWSI image, which were post-harvest remnants of a melon crop whose irrigation had been stopped two weeks before. The gray area just left of center at the bottom of the field indicated leakage of the drip system in the vicinity of the flush-out manifold. White areas on the image represented VIT points that fell outside the bounds of the trapezoid. These seemed to occur most often with artificial structures and open water (extreme right side of CWSI image), which can produce abnormally low vegetation indices.

INTERPRETATION: While management practices were not altered by this data set, the imagery did confirm the efficacy of the treatments being applied. The method shows excellent potential for monitoring drip irrigation

systems for insufficient water application. The ability to discern wet soil surfaces in fields with incomplete vegetative cover also has the potential of detecting over-irrigation and wasteful system leaks.

Before the method can become commercially viable, a more complete understanding is needed of precisely where crops having varying amounts of cover and degrees of water stress lie on the VIT trapezoid, and the limits of the trapezoid itself. In addition, the images are currently registered and processed by a slow process that must be automated to allow delivery to the user in a reasonable time.

FUTURE PLANS: Work will begin immediately on the development of an upgraded digital camera system that will speed image acquisition and registration. An intensive field experiment will be designed with plants at different densities, degrees of water stress, and various soil surface moistures to allow better a understanding of the trapezoid concept.

COOPERATOR: Henry Brubaker, Martori Farms, Aguila, AZ.

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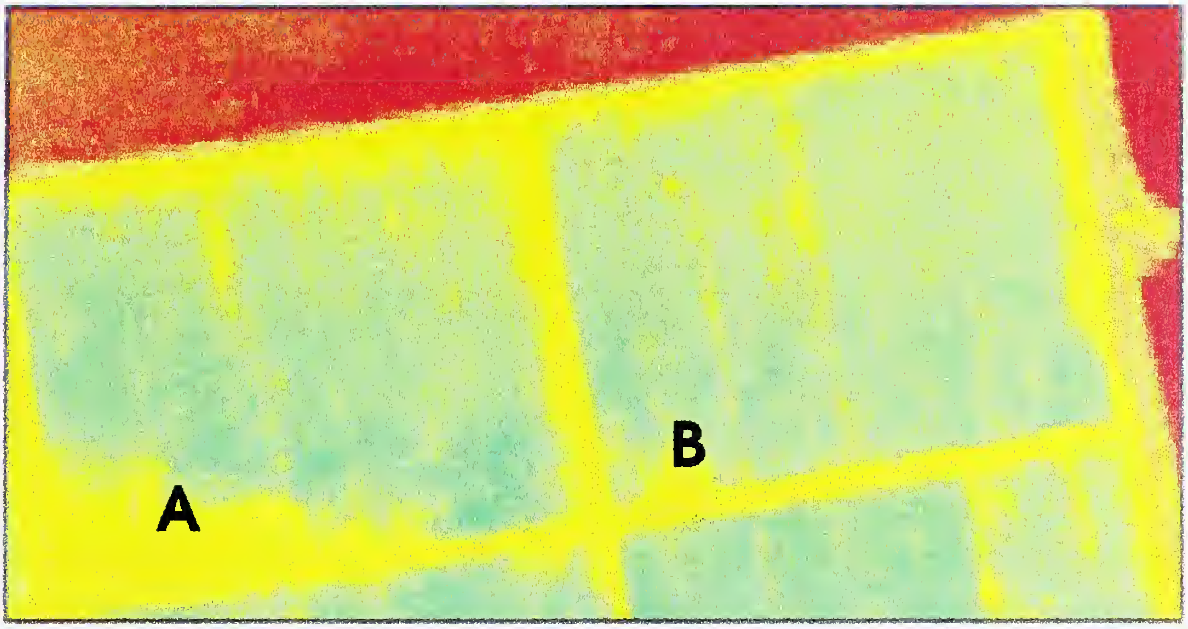


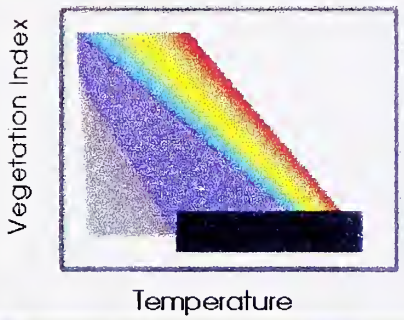
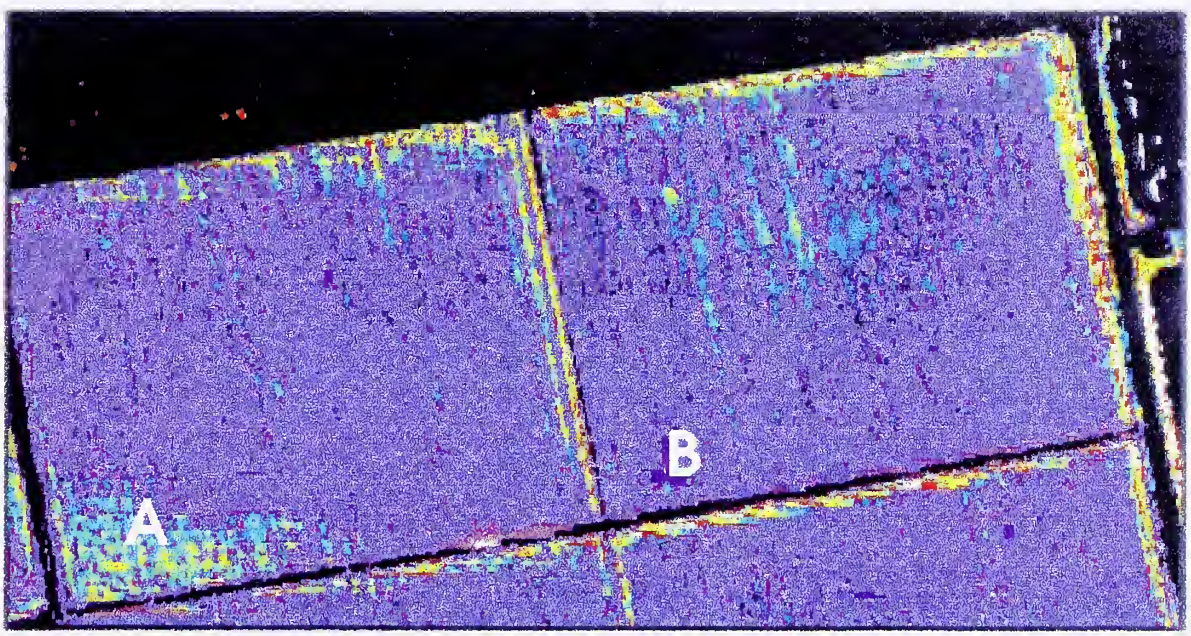


Figure 1a (above): Thermal image of a subsurface drip irrigated melon field, with two areas (A and B) recently treated for clogged emitters. Cool temperatures are shown as green, warm as yellow, and hot areas are red. Exposed soil contributed to the warm tempuratures seen in the problem areas. **Figure 1b** (left): The VIT trapezoid classified for water stress. Gray indicates a wet soil surface, blue is no stress, red is high water stress, and black is little to no vegetation. **Figure 1c** (below): CWSI image showing only mild water stress in area A and no water stress in area B, indicating effective treatment.



GERMPLASM IMPROVEMENT AND CULTURAL DEVELOPMENT OF NEW INDUSTRIAL CROPS

GUAYULE LATEX EXTRACTION AND GERMPLASM IMPROVEMENT

F.S. Nakayama, Research Chemist; and D.A. Dierig, Research Geneticist

PROBLEM: The production of large quantities of guayule latex, a hyperallergenic rubber source for medical and other consumer products, requires the development of new technology. Fabricators are keenly interested in making latex products from guayule, but the quantities presently available are limited and the appropriate specifications of the latex for manufacturing purpose have not been defined. Since the latex extracting procedures have not been firmly established, information on process optimization must also be derived. The latex extraction process must be followed carefully from shrub treatment to final product fabrication since the latices are subjected to various types of degradation conditions. This requires a careful monitoring of the steps taken for recovery. Information is also lacking on the yield component, namely the relationship between latex extraction and variety, which is needed for the selection and breeding improvement program. The objectives of this study are (a) to develop guayule latex rubber extraction methods for optimizing its quality and quantity, (b) to produce sufficient quantities of latex for trial studies by manufacturers of latex products, and (c) to improve the guayule lines for maximizing latex yields.

APPROACH: Various physical and chemical factors will be used to determine the extractability of latex from the shrub. For the initial phase, the extraction procedure and the effects of different types of shrub treatments will be examined from which a scaled-up process can be developed for producing large quantities of guayule latex suspension for fabricating rubber products. Different guayule lines will be investigated for their total rubber and latex-yielding capabilities and appropriate selections made from the data generated.

Latex Extraction: A flow diagram (fig. 1) depicts the major steps followed in latex preparation applicable for laboratory and field use. The parameters followed by question marks refer to variable items that may play an important role in latex extraction. For this initial phase, only five-year old plants were used. The shrubs were pollarded and the stem separated from the leaves and dead matter and the stems cut into smaller sections. Laboratory batch procedure was used to prepare guayule latex. The procedure consisted of macerating stem material in a water-based solution of a mixture of antioxidant and resin binder. The ground, filtered material containing the raw or crude latex was made alkaline (pH 10) to prevent latex coagulation and microbial decomposition. The crude latex mixture was centrifuged on a low capacity commercial cream separator to separate the latex from the rest of the serum material. The crude and refined latices were sent to our cooperator (Schloman) for characterizing their chemical and physical properties.

For the preparation of large quantities of latex, harvested whole shrubs were drenched with extracting solution and simultaneously ground in a hammer mill. The crude latex was cleaned up with a low capacity, industrial type separator and further purified by a creaming procedure.

Guayule Germplasm: Sixty lines resulting from diploid maternal plants crossed with high rubber-yielding tetraploid paternal plants were planted in April 1994 at the Maricopa Agricultural Center. Yields from these lines will be compared with standard check and other high-yielding lines from previous yield trials. Four different lines were asexually propagated by tissue culture for use in determining environmental effects on rubber and resin yields and other plant growth characteristics.

Latex yield determination of different lines has begun for developing relations between latex and total rubber content of the shrub. Three-year-old plants from three different breeding lines (C16, P10-4, N6-4), along with the 11605 reference line, were harvested to examine the relationship between extractable latex and solid rubber content. Plants were from a Completely Randomized Design experiment using four replications. Eight plants (two from each replication) of each line were harvested and analyzed for both resin and solid rubber content and latex. Three subsamples of each plant were analyzed.

FINDINGS: Latex Extraction: Approximately 2,270 Kg (5,000 lb) of guayule shrub were processed in early spring from which about 27 L (7 gal) of purified latex rubber suspension with 40% latex composition were produced. The processing of the shrub was made possible by using an industrial-size hammer mill for grinding the whole shrub and also a hydraulic press to extract the remainder of the solution from the plant-solution mixture or bagasse. However, some unanticipated problems were encountered in the latex preparation. Large amounts of soil and unground plant tissue drastically slowed the refining of the crude latex. The centrifuge separator had to be dismantled frequently to clean out the debris caught in the separation discs. Use of a larger centrifuge with automatic cleaning should improve and speed the latex extraction process. Nevertheless, enough latex solution was

obtained, and part of it was sent to the Polymer Science Department of the University of Akron for characterizing the physical and chemical properties of the latex. Arrangements have been made with a commercial fabricator to produce medical latex products.

We have been able to prepare about 0.5 liter of crude latex per week in the laboratory using laboratory-size grinders and dairy-type cream separators. Laboratory extraction procedures, however, are producing 1.5% latex yield, whereas our first attempt of field separation of latex was about 0.5 %. In either instances, yields can be significantly increased. The flow diagram of figure 1 indicates where additional studies can be made to improve the extraction process. In terms of the plant itself, we need information on latex yield as related to variety, age of plant, and time of harvest. Plant grinding is also important, since we need to grind the plant as finely as possible to get the rubber out of the cell, yet not fine enough that the grinding will break down the rubber polymer. Data are needed for preventing rubber oxidation and coagulation to permit extended storage of the latex before product manufacturing is undertaken. The proper method of separation of the latex from the serum using such techniques as creaming or centrifugation or their combination must be determined. The final latex product must be evaluated with close cooperation of the fabricators to meet their special criteria for producing the latex product. Finally, the biological properties of the latex and its products must be monitored to insure their hyperallergenic property.

Guayule Germplasm: Latex contents for all the samples ranged from 1 to 3%. Rubber content ranged between 7 to 12%, and resin from 7 to 14%. A larger amount of variation appears to exist between plants for both rubber and resin compared to latex content. These preliminary results show no interrelation between total rubber content and latex yields. Sufficient data are, however, unavailable to make any reliable conclusions at this time.

INTERPRETATIONS: Latex Extraction: Purified latex was produced for use by fabricators. However, large quantities of shrub and labor were required. Thus, the latex extraction process needs to be improved to obtain higher yields. Several areas for improvements, as indicated in figure 1, have been targeted for additional studies.

Guayule Germplasm: Although it was expected that a strong correlation would exist between total rubber and latex rubber, the results indicated that no relationship exists between these two rubber parameters. Additional studies are necessary using a larger number of lines and samples. Also, rapid extraction procedures and methods to insure latex stability in the shrub during the harvesting and processing must be developed.

FUTURE PLANS: Latex: Several modifications to the existing procedure will be explored for increasing the latex yield. These include the composition of the extracting solution, centrifugation and creaming techniques. Long-term studies will look at latex stability and use of antioxidants and other emulsion stabilizers. A rapid method will be developed for determining latex concentration. This is needed to monitor the entire latex extraction process while it is underway. A rapid and simple method for determining latex concentration will be examined. The guayule acreage will be increased by working with various cooperators to satisfy the future needs of the latex research and fabrication program.

Guayule Germplasm: Screening of other guayule lines for total rubber content and latex extractability will be made. Tissue-cultured lines will be transplanted into field plots in the spring to delineate the environmental effects on latex production.

COOPERATOR: K. Cornish, USDA-ARS-PWA, Albany, CA; W. Coates and J.J. Hoffman, Office of Arid Land Studies, University of Arizona; D.T. Ray, Plant Science Dept., University of Arizona, Tucson, AZ; W.W. Schloman, Jr., Dept. of Polymer Science, University of Akron, Akron, OH; R.A. Backhaus, Botany Dept., Arizona State Univ., Tempe, AZ; and M.A. Foster, Texas A&M Univ., Ft. Stockton, TX.

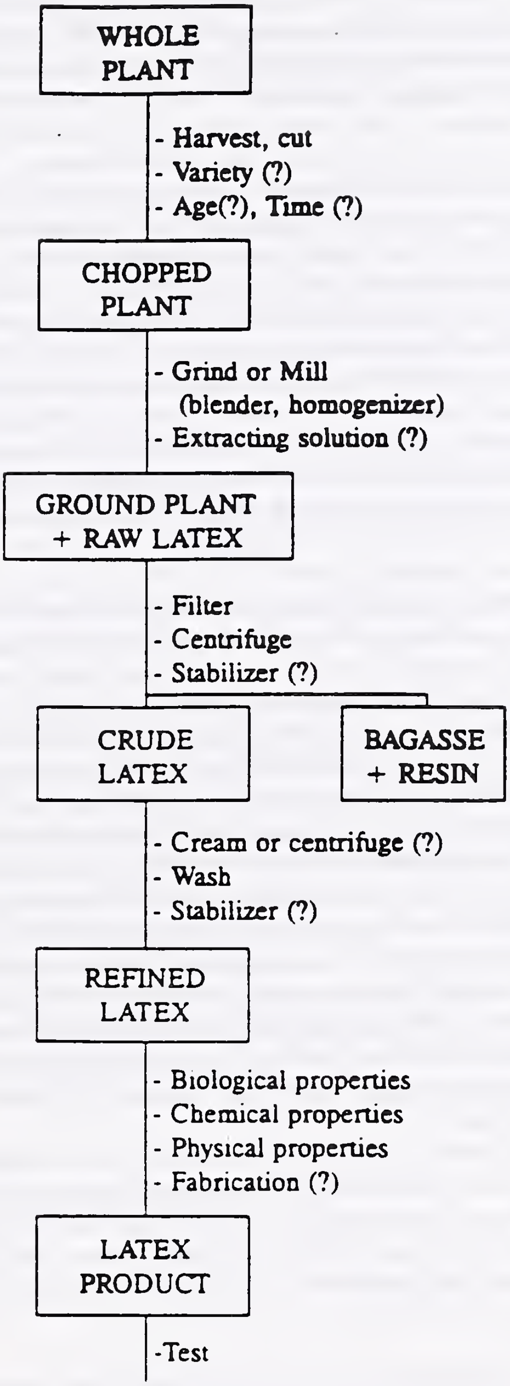


Figure 1. Flow diagram depicting the various processing steps used to obtain guayule rubber latex. Subject areas that need investigation are denoted by question marks.

LESQUERELLA GERMPLASM IMPROVEMENT AND COMMERCIALIZATION STATUS

D.A. Dierig, Research Geneticist; A.E. Thompson, Retired, Research Geneticist, Collaborator; F.S. Nakayama, Research Chemist; and D.J. Hunsaker, Agricultural Engineer

PROBLEM: Development of Lesquerella as a new industrial oilseed crop will contribute significantly to the improvement of U.S. agriculture and the general economy of the country. Since early 1970, the U.S. has relied exclusively on imports of castor for the supply of hydroxy fatty acids used in many types of industrial applications. Imports of castor oil and derivatives amount to more than 65,000 tons per year at a value exceeding $100 million per year. The unique chemical structure of the oil from Lesquerella offers distinct advantages for development of new industrial applications as well as a partial replacement for castor oil. Genetic and agronomic research conducted at this laboratory since 1984 has stimulated interest and cooperative interactions with industry. As a result, full scale commercialization effort is now in progress through joint interaction among other USDA agencies, universities, and private industry. Outside funding for this research has been provided through the USDA, Alternative Agriculture Research and Commercialization (AARC) Center. AARC grants are repayable by industry based on the success of the project and are, therefore, awarded to projects that are the most promising or most likely to succeed. The partners of this agreement include two industry companies, USDA-ARS, National Center for Agricultural Utilization Research (NCAUR), Peoria, Illinois, and this Laboratory. Other funding comes from the Department of Defense "Advanced Materials from Renewable Resources Program" through USDA-CSRS, Office of Agricultural Materials. Lesquerella germplasm base must be expanded and we are in the process of collecting seed throughout the U.S., which is partially funded by USDA-ARS, Plant Exploration Office. The focus of our research is to collect, evaluate, and improve Lesquerella germplasm; and to develop appropriate cultural and water management practices.

APPROACH: An extensive data base of locality information has been compiled from herbaria across the U.S. on Lesquerella and Physaria species. Germplasm collection for 1994 concentrated in Texas, Oklahoma, and Washington state. Along with seed collection, data on seed size, growth habit, and other plant characteristics were collected. Flower buds, when available, were collected for chromosome counts, and seed sent to NCAUR, Peoria, Illinois for oil content and fatty acid profile analyses. Populations of *L. fendleri* collected over the past 2 years were planted at the USWCL this fall for seed increase and evaluation. Twenty-five of these had enough seeds for direct seed planting on field sites. Another 25 populations did not have adequate seed amounts and were planted in the greenhouse for later transplanting into outdoor field plots. These 50 populations will be isolated with screen cages. Plants within the enclosures will be pollinated with honey bees placed in the cages. The resulting population will be analyzed for oil content and quality, seed weight, growth characteristics, and seed coat gum content.

Recurrent populations for increased oil content, increased hydroxy fatty acid content, and, hydroxy fatty acid yield were harvested this spring. Five hundred plants from each population were harvested and the seed sent to NCAUR for analysis. The highest 10% of the population were chosen and planted for another round of selection this fall.

Open-pollinated lines with yellow instead of orange seed coats were planted at USWCL. This is a segregating population for the trait, so selections will be made to begin a pure line with yellow seed coat. The oil from these lines may be lighter in color, which would be preferred by the cosmetic industry. Quality and quantity of oil and gums from these lines will be examined.

Studies to eliminate the need for insect pollinators for Lesquerella are continuing. Seed of autofertile progeny were planted in the greenhouse this fall. These selections include germplasm from our program and from Mycogen. These plants will be kept in isolation to verify that they are autofertile; seed will then be increased.

Molecular markers are being developed using RAPDs. The methodology for DNA extraction is completed and primers producing polymorphisms are being screened. Codominant isozyme markers are continuing to be used in genetic inheritance studies such as male sterility.

FINDINGS: A total of 9 species, 88 accessions, were collected from Texas including *L. argyraea* (12 accessions), *L. densiflora* (2 accessions), *L. fendleri* (46 accessions), *L. grandiflora* (6 accessions), *L. lasiocarpa* (7 accessions), *L. lindheimeri* (4 accessions), *L. purpurea* (4 accessions), *L. recurvata* (6 accessions), and *L. sessilis* (1 accession). Seven accessions were collected in Oklahoma. Because it was late in the season before we were able to collect in Oklahoma, we have only a limited amount of seed and inconclusive identification of species collected. Seven populations of *L. douglassii* were collected in diverse parts of Washington state. These plants were very productive

and provided relatively large quantities of seed. A summary of the oil analyses and seed weight of these species is shown in table 1.

The oil content range of the 500 samples from the recurrent population was between 17 and 33%. The range from the previous year was between 19 and 27%. Part of this increase may be attributed to environmental factors, since the range in the fatty acid content decreased slightly. However, the overall oil yield increased and is an indication that genetic gains are being achieved through this recurrent breeding strategy.

Other field research plots during the 1993-94 growing season include experiments to develop a crop water stress index to aid in scheduling irrigations, dates of planting, effects of nitrogen applications on seed yield, and herbicide studies (results of these studies are outlined in "Cultural Management of Lesquerella: Water and Stree Management," in this report).

INTERPRETATION: The major role of the USWCL research effort is to provide the lead in new germplasm collection, evaluation, genetic enhancement, and development of improved varieties or hybrids. This aspect of our program is being achieved. An adequate representation of the native southwestern U.S. populations have been completely collected, along with part of the Northwest. Through the collection effort of the past 2 years, we have added 9 species not previously entered into GRIN (Germplasm Resources Information Network) and 86 new populations of *L. fendleri*. This greatly improves the amount of diversity from which we can draw in our breeding program. It also will be important for the future development of potential markets for other Lesquerella species containing other types of hydroxy fatty acids.

The achievement of increasing oil content through recurrent selection is encouraging. The range of oil content for *L. fendleri* collected in the wild (see table) is not as high as this recurrent population. This demonstrates that the actual genetic potential is a lot greater than that seen in the initial screening of the collection material.

Continued research on water use efficiency and timing of water application is clearly needed along with other agronomic research. The additional support from the "Advanced Materials from Renewable Resources Program," DoD, through USDA-CSRS-OAM, will facilitate this by providing funding for our university cooperators. The infusion of AARC funding into our program will greatly help the germplasm evaluation program.

FUTURE PLANS: Germplasm collections for 1995 are planned for Tennessee, Alabama, Mississippi, and with recollection in Oklahoma. Species found in these areas contain densipolic hydroxy fatty acid in their seed oil with the exception of the Oklahoma species. More than half of the *fendleri* collections, along with a limited number of other species, are being grown-out for seed increase and preliminary evaluation at this location.

The next generation of the recurrent selection for improved oil and fatty acid content has been planted. Seed will be harvested and analyzed at this laboratory in June 1995. Seed and oil characteristics of yellow seed coat lines will be studied this season along with continued development of autofertile lines. Molecular marker development is in progress, and we plan to continue this work for use in germplasm evaluation and germplasm improvement.

COOPERATORS: R. L. Roth, Univ. Arizona, Tucson, AZ; J.H. Brown, J.D. Arquette, and K. Dwyer, International Flora Technologies.Apache Jct., AZ; M. Pollard, A. Hill, L. Sernyk, Mycogen Plant Sciences, San Diego, CA; E. H. Erickson, G.M. Loper, USDA, ARS, Carl Hayden Bee Research Laboratory, Tucson, AZ, L. Francois, USDA,ARS, U.S. Salinity Laboratory, Riverside, CA; R. Kleiman, B. Phillips, USDA, ARS, NCAUR, Peoria, IL.

Table 1. Mean, population variance, and range for seed and oil characteristics of lesquerella species collected in 1994 from Texas (with exception to *L. douglassii*, collected in Washington).

L. argyraea 8 populations	1000 seed wt. (g)	Oil Content (%)	Lesquerolic Acid (%)
Mean	0.54	23.8	55.8
pop. var.	0.010	5.0	3.3
range	0.45 - 0.67	21.2 - 26.3	53.3 - 58.4

L. densiflora 1 population	1000 seed wt. (g)	Oil Content (%)	Lesquerolic Acid (%)
Mean	0.59	NA	64.8

L. douglassii 7 populations	1000 seed wt. (g)	Oil Content (%)	Lesquerolic Acid (%)
Mean	1.56	26.2	47.3
pop. var.	0.059	25.2	15.5
range	1.37 - 1.91	22.4 - 37.4	40.0 - 52.6

L. fendleri 41 populations	1000 seed wt. (g)	Oil Content (%)	Lesquerolic Acid (%)
Mean	0.56	24.1	50.6
pop. var.	0.009	8.1	11.7
range	0.34 - 0.75	17.3 - 28.7	41.9 - 58.6

L. grandiflora 3 populations	1000 seed wt. (g)	Oil Content (%)	Lesquerolic Acid (%)
Mean	0.68	NA	54.8
pop. var.	0.016	NA	1.5
range	0.59 - 0.77	NA	53.4 - 55.8

L. lasiocarpa 2 populations	1000 seed wt. (g)	Oil Content (%)	Lesquerolic Acid (%)
Mean	0.49	19.5	49.1
pop. var.	0.004	NA	15.1
range	0.43 - 0.55	NA	46.3 - 51.8

L. lindheimeri 1 population	1000 seed wt. (g)	Oil Content (%)	Lesquerolic Acid (%)
Mean	0.78	NA	76.5

L. purpurea 3 populations	1000 seed wt. (g)	Oil Content (%)	Lesquerolic Acid (%)
Mean	0.48	20.4	52.1
pop. var.	0.001	0.7	5.6
range	0.46 - 0.50	19.8 - 21.0	49.9 - 54.6

L. recurvata 6 populations	1000 seed wt. (g)	Oil Content (%)	Lesquerolic Acid (%)
Mean	0.50	20.5	63.5
pop. var.	0.003	2.6	22.8
range	0.45 - 0.58	19.5 - 22.4	56.4 - 69.7

L. sessilis 1 population	1000 seed wt. (g)	Oil Content (%)	Lesquerolic Acid (%)
Mean	0.48	NA	69.8

CULTURAL MANAGEMENT OF LESQUERELLA: WATER AND STRESS MANAGEMENT

D.J. Hunsaker, Agricultural Engineer; W.L. Alexander, Agronomist;
D.A. Dierig, Research Geneticist; F.S. Nakayama, Research Chemist;
and A.E. Thompson, Research Geneticist

PROBLEM: Prior studies have indicated a seasonal water use requirement of about 600 mm for lesquerella in central Arizona. However, the effects of irrigation frequency on lesquerella seed yields are not well understood. Early studies on yield response to irrigation indicated greater yields when water was applied at low than high frequencies. However, more recent studies have also shown that water stress during flowering and seed development can reduce yields. Results from 1992-93, indicated no difference in seed yield between plots irrigated every seven days and plots irrigated every 12-14 days. This same study also indicated a slight reduction in yield for plots subjected to water stress during different stages of crop development. The current effort was aimed at gaining greater insight on the effects of irrigation frequency on the yield of lesquerella. Another objective was to evaluate the effects of supplemental nitrogen application on yields.

APPROACH: Two field experiments were conducted during the 1993-94, lesquerella growing season at The University of Arizona, Maricopa Agricultural Center. The 0.4-ha field site was divided into two sections consisting of 24 plots planted on the flat on 22 September 1993, and 24 plots planted in beds (1.0-m row spacing) on 19 October 1993. Each plot was 8 by 10 m. The seeding rate was 6.7 kg ha^{-1} for both experiments. Following planting, the plots planted on the flat were sprinkler irrigated several times with a total of 50 mm of water for seed germination and crop establishment. However, it was necessary to apply more water (a total of 165 mm) to the bedded plots following planting to ensure adequate moisture to the seeds.

The experimental design in both experiments was a complete two-factorial design, replicated four times, containing three levels of irrigation [every seven days (weekly), every 14 days (biweekly), and every 21 days (triweekly)] and two levels of nitrogen application (high and low). The irrigation treatments were begun in mid-March 1994. Metered water applications were applied by surface irrigation with quantities ranging from 95 to 115 mm per irrigation to the flat plots and from 65 to 90 mm per irrigation to the bedded plots. Plots of the low nitrogen treatment were given one application of 56 kg-N ha^{-1} in mid-February 1994, while plots of the high nitrogen treatment were given two applications of 67 kg-N ha^{-1} in mid February and mid March 1994. The plots were top-dressed with ammonium nitrate and then irrigated for incorporation into the soil.

Soil water content was monitored over the growing season in each plot using neutron scattering and time domain reflectometry equipment. A 2 by 10 m section near the center of each plot was harvested by combine on 15 June 1994. The harvested seed was then cleaned and weighed. Additional 1.0-m^2 sample areas established in each plot were hand harvested by clipping. Total aboveground plant dry weights were determined before threshing the seed.

FINDINGS: Biweekly and triweekly irrigation treatments received 77 and 68% of the total water applied given to the weekly treatment in the flat-planted plots, and 82 and 75% of that given to the weekly in the bed-planted plots (table 1). However, even triweekly plots received a total water application of over 600 mm, the estimated water use requirement of lesquerella. Soil water content was considerably lower over the biweekly and triweekly irrigation treatments compared to the weekly treatment (figure 1), particularly during late March through April 1994.

Analysis of seed yield data indicated no statistical difference between irrigation or nitrogen treatments (table 2). However, there was a significant increase (12-22%) in plant dry weight for the high nitrogen treatment over the low nitrogen treatment. Analysis of seed size and seed oil content has not been completed.

A crop coefficient curve, that relates crop evapotranspiration to reference crop evapotranspiration, was developed for lesquerella from soil water measurements taken over four studies between 1991-1994.

INTERPRETATION: The seed yield of lesquerella was not affected by irrigation frequency and total water applied during 1993-94. These results support most of the earlier studies on irrigation management. It has been suggested that high-frequency irrigation may reduce fertility due to possible leaching effects. However, the additional nitrogen application in the current experiments did not increase yield under weekly irrigation, although it did increase plant biomass. It was unexpected that the triweekly irrigation treatment attained the same seed yield as the other irrigation treatments. Last year's experiment indicated a slight reduction in seed yield when irrigation was withheld for up

to three weeks during late flower (April). Collectively, all the data obtained from lesquerella irrigation research during the past four years suggests that optimum seed yields may be obtained with irrigation given about every two-weeks between late February through May. However, the amount of water applied during the growing season must be sufficient to meet the water use requirement of approximately 600 mm.

FUTURE PLANS: The crop coefficient curve for lesquerella will be used to schedule irrigation time and amounts during the 1994-95 growing season.

COOPERATORS: J. Nelson, Agronomist, The University of Arizona, Maricopa Agricultural Center.

Table 1. Total water applied for irrigation treatments in 1993-94.

Planting Method	Irrigation Treatment	Number of Irrigations[1]	Total Water Applied [2] (mm)
	Weekly	10	990
Flat	Biweekly	7	765
	Triweekly	6	675
	Weekly	10	850
Bed	Biweekly	7	700
	Triweekly	6	635

[1] Does not include irrigations given for crop establishment.

[2] Includes irrigation for crop establishment plus 60 mm of rainfall.

Table 2. Seed yield and plant dry weight for irrigation and nitrogen treatments in 1993-94.

Irrigation Treatment	Nitrogen Treatment	Seed Yield (kg/ha)		Plant Dry Weight (kg/ha)	
		Flat	Bed	Flat	Bed
Weekly	High	1320	970	10080	8105
Weekly	Low	1470	960	8475	7030
Biweekly	High	1220	1030	9625	8160
Biweekly	Low	1555	1075	8900	7055
Triweekly	High	1510	924	10725	7330
Triweekly	Low	1400	980	7600	7025

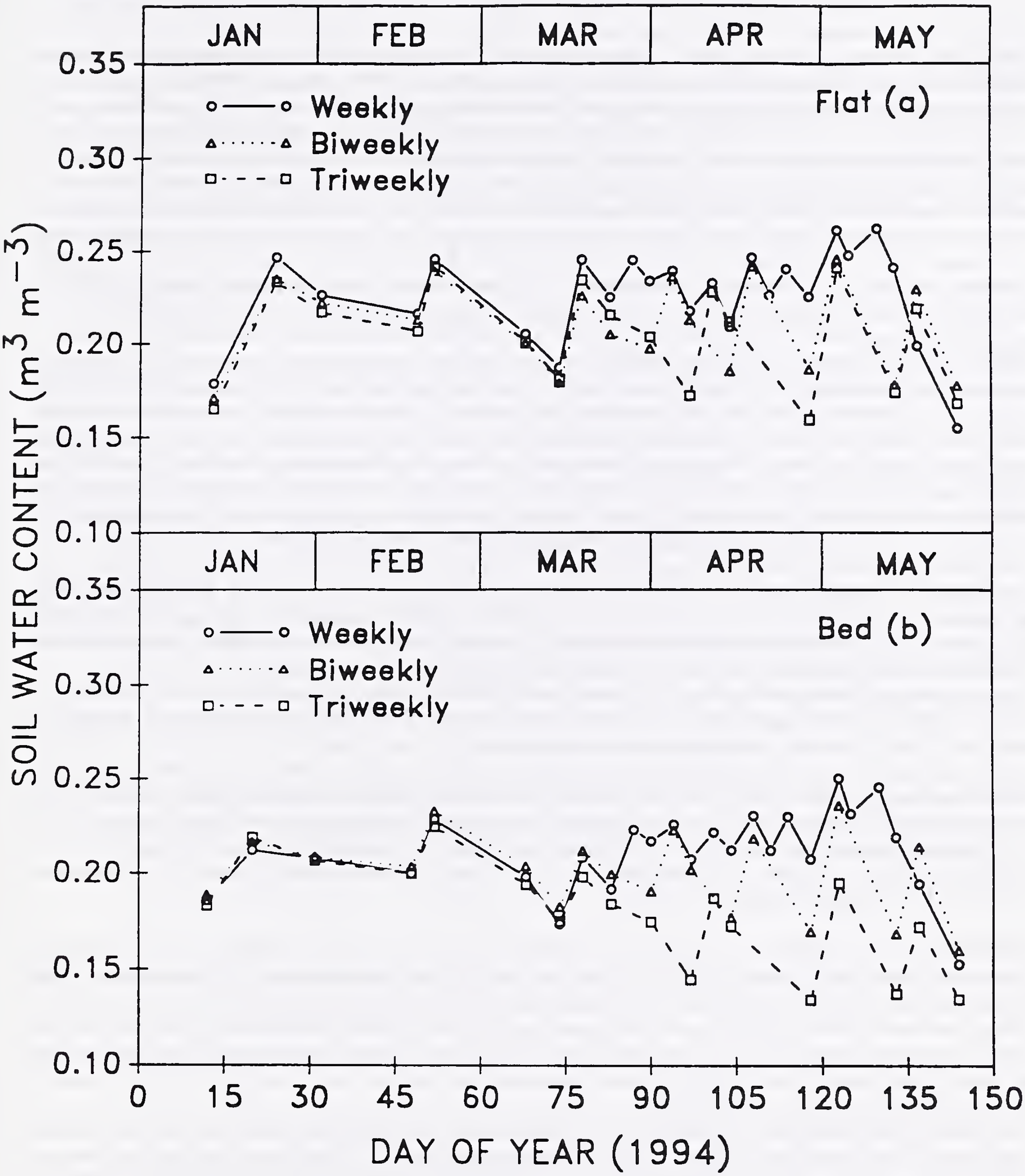


Figure 1. Soil water contents (0 to 1.1-m) with time for irrigation treatments in flat (a) and bed (b) planted fields in 1993-94.

VERNONIA GERMPLASM IMPROVEMENT

D.A. Dierig, Research Geneticist; A.E. Thompson, Retired, Research Geneticist, Collaborator; F.S. Nakayama, Research Chemist; and D.J. Hunsaker, Agricultural Engineer

PROBLEM: Natural epoxidized oils are potentially important for industrial use as drying agents in reformulated oil-based or alkyd-resin paints. The United States presently manufactures 1230 million liters of these types of paints and varnishes annually. Drying agents currently used in them are major air pollutants, releasing volatile organic compounds (VOCs). Use of vernonia oil in these formulations would greatly reduce the VOC pollutants and create some 150,000 ha of an alternative crop for farmers to grow. *Vernonia galamensis* is one of the small number of plants that contain and produce enough epoxidized oil to make it highly promising for commercialization. *V. galamensis* is a native of Africa and flowers and produces seed only under short-day conditions. This characteristic has prevented successful cultivation of Vernonia within the continental U.S. However, we have successfully utilized an accession, subspecies *galamensis*, variety *petitiana*, that will flower any time of the year, to produce hybrids containing this trait. The objective of this research is to develop high-yielding germplasm adapted to the U.S. through hybridization and selection and to evaluate Vernonia's agronomic potential as a new oilseed crop.

APPROACH: Flowering and seed yield of 31 F4 lines planted at The University of Arizona Maricopa Agricultural Center and 11 also planted at Safford, Arizona, were evaluated and compared to the day-neutral parent. Nine of these lines were planted at four other locations; Medford, Oregon; Ft. Stockton, Texas; Columbia, Missouri; and Petersburg, Virginia; for additional evaluation. The cooperators collected flowering data over a 5-week period for comparisons among locations. Different population densities were obtained at Maricopa, Arizona, by varying the plant spacing within the row, which was 1 m apart. Plant populations were established at 15,000, 30,000 and 60,000 plants per ha using spacings of 0.15 m, 0.30 m, and 0.60 m, respectively, in a CRB design with 4 replications. Water use was monitored in these plots using neutron scattering equipment.

A greenhouse experiment compared long- and short-day treatments on three hybrid lines and their parents. The parent lines were A0382, flowering only under short days, and A0399 flowering under any daylength. The long day treatment was exposed to 14 hours of daylength and 10 hours of dark. The short day was exposed to 10 hours of light and 14 hours of dark. Daylength was controlled by placing a black cloth over the plants. Treatments were compared by counting the number of flower heads per plant at the end of the experiment.

Autofertility was determined on the 31 hybrid lines by hand self-pollinations made in the greenhouse. Autofertility is a desirable trait that we would like to incorporate into Vernonia so pollinators will not be needed. Pollen tube growth was also examined from controlled crosses.

Molecular markers are being developed using RAPDs. DNA is extracted from a plant and increased by Polymerase Chain Reaction (PCR). This technique allows DNA fragments from different plants to be compared between different plants, in the same way a phenotypic marker, such as flower color, could be compared.

Seed has been sent to ARS, NCAUR, Peoria, Illinois for analysis. GC and NMR equipment has been purchased for doing in-house oil analyses. Selections made here and at other locations are being increased over the winter at the USDA-ARS facility, Isabela, Puerto Rico.

FINDINGS: Sixty-one days after planting eight hybrid F4 lines had the same or a higher percentage of plants flowering as the day-neutral check. Eighty-nine days after planting, the average number of plants flowering of all 31 lines was 82%. Ninety-seven percent of the plants in the check line were flowering by this date, and six of the hybrid lines were equal to the check line. The cooperators at the four other locations collected the same data on flowering over a five-week period on a seven day interval. The results from the third week (72 days after planting) are shown in the graph. Seed yields, oil content and quality, and seed size and retention, will be correlated to growth and flower characters after harvest.

In terms of plant population, no effect on the number of plants flowering within a line was observed between plants spaced 0.15 m and 0.30 m apart. The 0.6-m spacing treatment had 85% of plants in flower compared to 31% in the other two spacing treatments. However, no differences between the three treatments for number of plants flowering was present two weeks later. Plant water use, as measured by soil water depletion during late June, late July, and mid-August was 8% and 30% higher on average for the 0.15-m spacing compared to the 0.30 m and 0.60 m respectively. However, there was no difference in the estimated plant water extraction depth between

the three spacings. The maximum depth reached was about 1.5 m during late July. The water use rates for the 0.15-m spacing averaged 6.5 mm/day in late June, 8.3 mm/day in late July, and 7.1 mm/day in mid-August.

The greenhouse daylength experiment demonstrated that short-day treatments greatly increased the number of flower heads, and therefore, the amount of seed produced from each plant. The A0399, which flowers under any daylength, produced twice as many flowers in the short-day treatment as long day treatment. An average of 60 flower heads per plant were produced under short days, compared to 28 flower heads per plant under long days. The other parent, A0382, as expected, did not flower under long days and only produced an average of five flowers per plant under short days. All hybrids initiated flowers under both conditions, but generally had four-to-five times more flowers in the short-day treatment compared to the long day.

The results from greenhouse hand pollinations indicated that variation for autofertility exists both within and between hybrid lines. Autofertile plants have been identified and viable seed collected for further studies. Male sterility has been identified in a few hybrid plants. These male sterile plants may have potential use in the future for hybrid production.

INTERPRETATION: Hybrid lines have been identified that have nearly the same flowering response as the donor parent of this trait, A0399 var. *petitiana*. The greenhouse daylength experiment indicated that even though the timing of flowering was the same in the hybrids compared to this parent, the number of flowers initiated is still quite variable. A0399 cannot be strictly called a day-neutral variety since a response in the number of flower heads produced is dependent on daylength. However, variation was seen within this variety, allowing further selection and backcrossing onto the hybrids. The barrier to growing Vernonia in the U.S. has been overcome through this hybridization, but improvement is still necessary for future commercialization.

Although plants may have flowered earlier in the 0.60-m spacing, toward the end of the season, those plants appeared to be the poorest performers. As plants mature the stem become brittle. There seems to be an advantage to spacing plants closer, possibly to provide support for other plants. The closer spacing may also force flowering on the top and outside canopy, allowing better plant architecture for harvesting.

FUTURE PLANS: Financial support from the "Advanced Materials from Renewable Resources Program" from the Department of Defense, through the CSRS, Office of Agricultural Materials was obtained for a second year (FY95) to support Vernonia research. These funds are being utilized to support faster germplasm increase through the winter nursery in Puerto Rico, and cooperation at other locations. We plan to continue the greenhouse studies of the floral biology and the development of molecular markers. In spring 1995 we will grow-out selections presently being increased in Puerto Rico. These will be evaluated at the same locations as this past year. Development of cultural practices for the various locations will be expanded.

COOPERATORS: R. Kleiman and B. Phillips, USDA-ARS-NCAUR, Peoria, IL: D.T. Ray, Univ. of Arizona, Tucson; M.A. Foster, TAES, Texas A&M, Ft Stockton, TX; R.J. Roseburg, Oregon State Univ., Medford, OR; R.L. Myers, Univ. of Missouri, Columbia, MO; H.L. Bhardwaj, Virginia State Univ., Petersburg, VA;

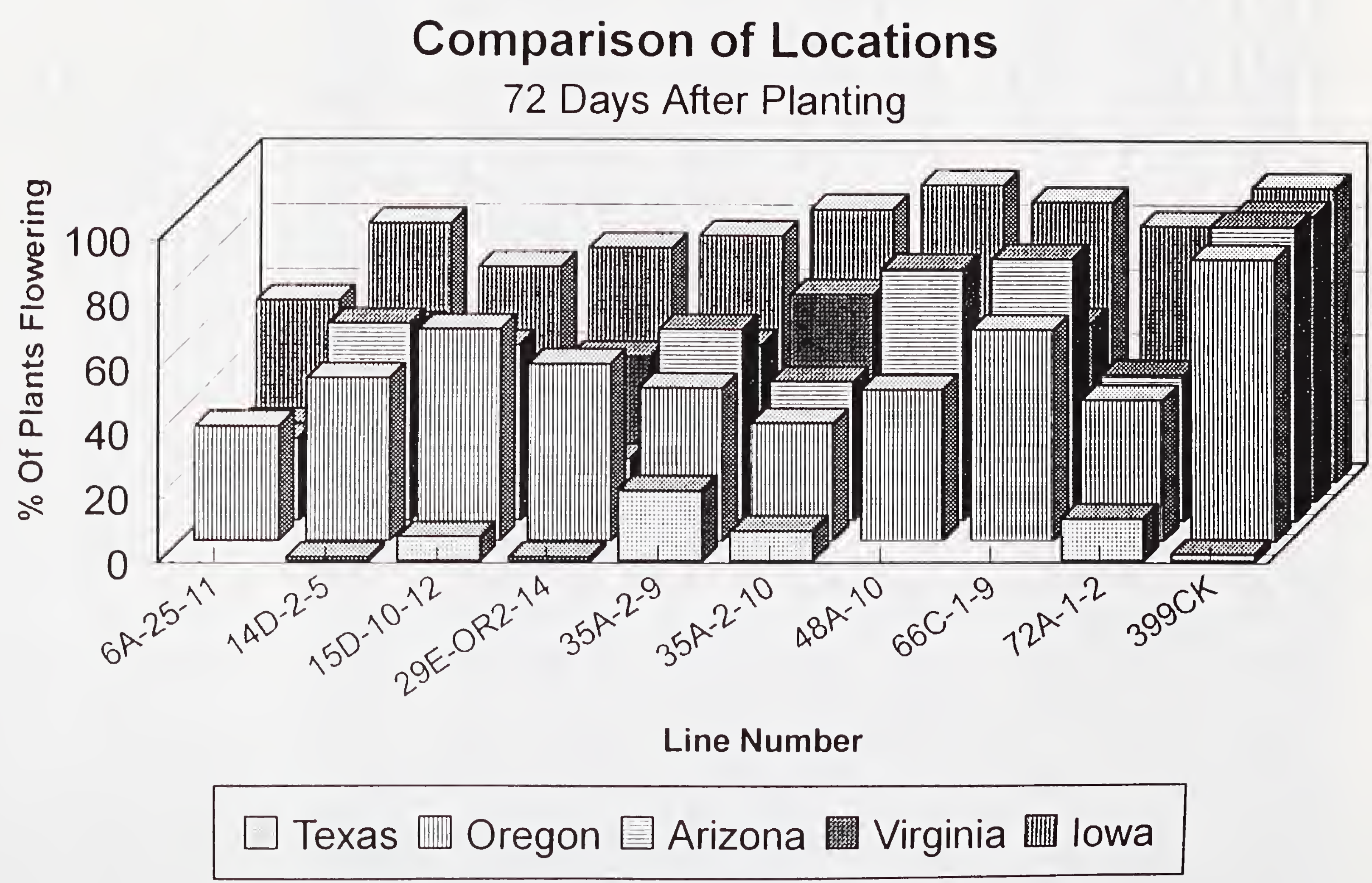


Table 1. Mean, population variance, and range for seed and oil characteristics of lesquerella species collected in 1994 from Texas.

LABORATORY SUPPORT STAFF

ELECTRONICS ENGINEERING LABORATORY

Dean E. Pettit, Electronics Engineer

The Electronics Engineering Laboratory is staffed by an Electronics Engineer whose duties include design, development, evaluation, and calibration of electronic prototypes in support of U.S. Water Conservation Laboratory research projects. Other responsibilities include repairing and modifying electronic equipment and advising staff scientists and engineers in the selection, purchase and upgrade of electronic equipment.

Support provided to research in 1994 include:

- Redesign and construction of a multi-valve, 16 channel switch controller to interface to OMNIDATA's EZ Logger data collection unit (see Hunsaker, Clemmens and Alexander, "High Frequency, Small-Volume Level Basin Irrigation for Cotton" in this report).

- Development of a differential radio receiver unit interface to adapt the portable Global Positioning system for increased accuracy. The design includes a portable battery power source, a variety of FM antennas and cable connections (used in MADMAC and FACE projects).

- Design, modification, and construction of a portable Ni Cad and Lead Acid battery load tester and deep cycle discharger. The load tester functions on multiple ranges and has the ability to measure battery conditions under loaded vs. unloaded conditions (used for the MADMAC project).

- Design and installation of a modification and interface to the new phone system for the machine shop phone paging system.

- Development of an original design of Opportunity Timers utilizing a micro-programmable computer chip as the time keeper, storage unit, and event watch dog. The display was reduced to one liquid crystal display module. The new design is being tested at the time of this report.

Repairs and recalibration in 1994 included CO2 analyzers, a Beckman centrifuge, process grinders, a power voltage regulator, and modification and replacement of switching relays for the FACE project.

COMPUTER FACILITY

Terry A. Mills, Computer Specialist

The Computer Facility is staffed by a full-time Computer Specialist and a Computer Assistant. Support is provided to all Laboratory and Location Administrative Office computer equipment and applications. The facility is responsible for recommending, purchasing, installing, configuring, upgrading, and maintaining the Laboratory's Local and Wide Area Networks (LAN, WAN) computer systems and peripherals. The LAN is composed of seven 10Base-T hubs connected to a standard ethernet backbone providing 88 ports. A local router and a 56kbs lease line to Arizona State University provide a gateway to the INTERNET WAN. The Laboratory has an INTERNET Class C IP address and operates under the domain uswcl.ars.ag.gov. Network UNIX services are provided by a SunMicro Sparc Station II and a SunMicro Sparc 20. Two Novell Netware 3.12 servers currently provide most of the file, communication, and printing services. Laboratory personnel are currently working with DOS, OS/2, and UNIX operating systems.

In 1994, establishing current and future requirements was the main focus of the computer facility. Providing better INTERNET access and E-Mail from desktop computers, disk storage, and backups were topics of concern.

Plans for 1995 include a continuing effort to integrate the LAN environment between UNIX, DOS/Windows, and OS/2. We are also preparing to evaluate the benefits of Micosoft's New Technology Advanced Server (NTAS) and multi-processor systems.

LIBRARY AND PUBLICATIONS

L. Susan Seay, Publications Clerk

Library and publications functions, performed by one Publications Clerk, include maintenance of records and files for publications authored by the Laboratory Research Staff, including publications co-authored with outside researchers,[1] as well as for holdings of professional journals and other incoming media. Support includes searches for requested publications and materials for the Staff. Library holdings include approximately 1600 volumes in various scientific fields related to agriculture. Holdings of some professional journals extend back to 1959.

The U. S. Water Conservation Laboratory List of Publications, containing almost 1900 entries, is maintained on PROCITE, an automated bibliographic program. The automated system provides for sorting and printing selected lists of Laboratory publications and is expected to be accessible on LAN by the Research Staff for that purpose later this year. Publications lists and most of the publications are available by phone or mail requests to the Publications Clerk.

A draft Auxiliary Laboratory Publications List has been compiled and will be available on request by April 1995. The Auxiliary List includes abstracts, presentation handouts, selected reports, and non-peer-reviewed materials to facilitate their wider dissemination and use.

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[1] Appendix A lists manuscripts published in 1994 and manuscripts formally accepted for publication.

MACHINE SHOP

C. L. (Bud) Lewis, Machinist

The machine shop, staffed by one full-time and one part-time machinist, provides facilities to fabricate, assemble, modify, and replace experimental equipment in support of U. S. Water Conservation Laboratory research projects. Following are examples of work orders completed in 1994.

An extension for the aluminum tank at the beginning of the glass channel in the hydraulics laboratory was fabricated and installed. The tank was raised to increase water flows in order to modify old, empirically calibrated Parshall flumes into calibrated broad-crested weirs. The extension was fabricated with 12.50"-high side boards of stainless steel sheet metal attached to a frame of aluminum angle. Shock-absorber mountings were modified and the channel cross brace was extended and reinstalled.

A modified root core sample tube was fabricated to obtain samples for root biomass measurements to study effects of elevated CO_2 levels on root growth and for soil chemical analysis as part of the Free-Air Carbon Dioxide Enrichment (FACE) project. The modified tube is 1.000 meter tall with a 4.250" OD and a 3.750" ID. It is fabricated from 304 stainless steel and has a removable cross-section port and a modified removable drive unit.

Two stilling wells were fabricated for head measurements for portable flumes. The wells were fabricated from 8.00" ID aluminum pipe with a 0.083" wall. They are 42.000" tall and have a removable instrument lid and a 1.250" flume connection.

APPENDIX A

APPENDIX A

Manuscripts Published in 1994 and Manuscripts Formally Accepted for Publication

1. ADAMSEN, F.J. 1993. Mineral composition of peanut as influenced by irrigation water quality and irrigation method. Commun. Soil Sci. Plant Anal. 24(5&6):525-538. WCL# 1789.[1]

2. ADAMSEN, F.J., and F.S. WRIGHT. 1994. Response of Virginia-type peanuts under conservational tillage to gypsum. Commun. Soil Sci. Plant Anal. 25(5&6):637-650. WCL# 1788.

3. AKIN, D.E., L.L. RIGSBY, G.R. GAMBLE, W.H. MORRISON III, B.A. KIMBALL, P.J. PINTER, JR., G.W. WALL, R.L. GARCIA, and R.L. LAMORTE. Biodegradation of plant cell walls, wall carbohydrates, and wall aromatics in wheat grown in ambient or enriched CO_2 concentrations. J. Sci. Food Agric. (ACCEPTED-NOV 1994). WCL# 1837.

4. AKIN, D.E., B.A. KIMBALL, W.R. WINDHAM, P.J. PINTER, JR., G.W. WALL, R.L. GARCIA, R.L. LAMORTE, and W.H. MORRISON III. Effect of free-air CO_2 enrichment (FACE) on forage quality of wheat. Animal Feed Sci. & Tech. (ACCEPTED-SEP 1994). WCL# 1838.

5. AKIN, D.E., B.A. KIMBALL, J.R. MAUNEY, R.L. LAMORTE, G.R. HENDREY, K.F. LEWIN, J. NAGY, and R.N. GATES. 1994. Influence of enhanced CO_2 concentration and irrigation on sudangrass digestibility. Agric. & Forest Meteorol. 70:279-287. WCL# 1756.

6. AL-AZBA, A., and STRELKOFF, T. 1994. Correct form of Hall Technique for border irrigation advance. J. Irrig. and Drain. Eng. 120(2):292-307. WCL# 1689.

7. ALLEN, R.G., G.L. DICKEY, J.L. WRIGHT, J.F. STONE, and D.J. HUNSAKER. 1994. Error analysis of bulk density measurements for neutron gauge calibration. p. 1120-1127. IN: 1993 Nat. Conf. Irrig. and Drain. Eng., ASCE, Park City, UT. 21-23 Jul 1993. WCL# 1762.

8. BHARRACHARYA, N.C., J.W. RADIN, B.A. KIMBALL, J.R. MAUNEY, G.R. HENDREY, J. NAGY, K.F. LEWIN, and D.C. PONCE. 1994. Leaf water relations of cotton in a free-air CO_2-enriched environment. Agric. & Forest Meteorol. 70:171-182. WCL# 1757.

9. BOUWER, H. 1994. Artificial recharge with treated sewage and soil-aquifer treatment. p. 243-257. IN: Proc. European Water Pollution Control Association (EWPCA), Conf. on Integrated Wastewater Management Collection, Treatment and Reuse, Lisbon, Portugal. 10-12 Oct 1994. WCL# 1827.

10. BOUWER, H. 1994. Global water concerns with local implications. p. 1-16. IN: Proc. 1994 Nevada Regional Alfalfa Symp., sponsored by Nevada Farm Bureau, Reno, NV. WCL# 1783.

11. BOUWER, H. 1994. Introduction to Artificial Recharge. p. 12-34, and Phoenix, Arizona Recharge Projects, p. 222-232. IN: Ground water recharge using waters of impaired quality, NAS-NRC-WSTB Committee, Nat. Acad. Press, 283 p. WCL# 1831.

12. BOUWER, H. 1994. Irrigation and global water outlook. Agric. Water Management. 25(3):221-231. WCL# 1816.

13. BOUWER, H. 1994. Issues in artificial recharge of groundwater. p. 1-7. IN: Salt River Project and U.S. Water Conservation Laboratory, Phoenix, AZ, and Water Resources Research Center, The University of AZ. Proc. Sixth Biennial Symp. on Artificial Recharge of Groundwater, Scottsdale, AZ. 19-21 May 1993. WCL# 1745.

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[1] The WCL# corresponds to the item number on the USWCL Publications List. Please use the WCL# to request USWCL publications.

14. BOUWER, H. 1994. Reducing surface water pollution by using sewage effluent for irrigation and other purposes. 5:53-64. IN: Water Management and Protection. American Inst. of Hydrology, Minneapolis, MN. Proc. Second USA/CIS Joint Conf. on Environmental Hydrology and Hydrogeology, Washington, DC. 16-21 May 1993. WCL# 1744.

15. BOUWER, H. 1994. Reuse of urban sewage for irrigation. p. 215-227. IN: Proc. European Water Pollution Control Association (EWPCA), Conf. on Integrated Wastewater Management Collection, Treatment and Reuse, Lisbon, Portugal. 10-12 Oct 1994. WCL# 1826.

16. BOUWER, H. 1994. Role of geopurification in future water management. p. 73-81. IN: G.W. Gee, C. Rosenzweig, D.M. Kral, M.K. Viney, and R.S. Baker (ed.) SSSA Special Publication Number 41, Madison, WI. Proc. of a Symp., Soil and Water Science: Key to Understanding Our Global Environment, sponsored by Divisions S-1 and S-6 of the Soil Sci. Soc. of Am., Cincinnati, OH. 10 Nov 1993. WCL# 1830.

17. BOUWER, H. 1994. Role of groundwater and artificial recharge in future water resources management. p. 491-497. IN: S.J. Soveri (ed.) Proc. Future Groundwater Resources at Risk, Helsinki, Finland. 13-16 Jun 1994. WCL# 1813.

18. BOUWER, H. 1994. Sustainable irrigated agriculture: Water resources management in the future. Irrig. J. 43(6):16-23. WCL# 1785.

19. BOUWER, H. 1994. Water reuse and groundwater recharge. p. 197-210. IN: Proc. 1994 Water Reuse Am. Water Works Assoc., and Water Environ. Fed. Symp. Dallas, TX. 27 Feb-2 Mar 1994. WCL# 1812.

20. CABOT, F., J. QI, M.S. MORAN, and G. DEDIEU. 1994. Test of surface bidirectional reflectance models with surface measurements: Results and consequences for the use of remotely sensed data. p. 627-634. IN: Proc. 6th Int. Symp. Physical Measurements and Signatures in Remote Sensing, Val d'Isere, France. 17-21 Jan 1994. WCL# 1795.

21. CLARKE, T.R., M.S. MORAN, Y. INOUE, AND A. VIDAL. 1994. Estimating crop water deficiency using the relation between surface minus air temperature and spectral vegetation index. p. 1021-1028. IN: Proc. 6th Int. Symp. Physical Measurements and Signatures in Remote Sensing, Val d'Isere, France. 17-21 Jan 1994. WCL# 1771.

22. CLEMMENS, A.J., G. SLOAN, and J. SCHUURMANS. 1994. Canal control needs: An example. J. Irrig. and Drain. Eng. 120(6):1067-1085. WCL# 1750.

23. DESOUSA, P.L., A.R. DEDRICK, A.J. CLEMMENS, and L.S. PEREIRA. The effect of furrow elevation differences on level-basin performance. Trans. ASAE. (ACCPETED-NOV 1994). WCL# 1737.

24. DICKEY, G.L., R.G. ALLEN, J.L. WRIGHT, J.F. STONE and D.J. HUNSAKER. 1993. Soil bulk density sampling for neutron probe calibration. p. 1103-1111. IN: 1993 Nat. Conf. Irrig. and Drain. Eng., ASCE, Park City, UT. 21-23 Jul 1993. WCL# 1761.

25. DUGAS, W.A., and P.J. PINTER, JR. 1994. Introduction to the free-air carbon dioxide enrichment (FACE) cotton project. Agric. & Forest Meteorol. 70:1-2. WCL# 1843.

26. DUGAS, W.A., M.L. HEUTER, D.J. HUNSAKER, B.A. KIMBALL, K.F. LEWIN, J. NAGY, and M. JOHNSON. 1994. Sap flow measurements of transpiration from cotton grown under ambient and enriched CO_2 concentrations. Agric. & Forest Meteorol. 70:231-245. WCL# 1682.

27. ESTIARTE, M., J. PENUELAS, B.A. KIMBALL, S.B. IDSO, R.L. LAMORTE, P.J. PINTER, JR., G.W. WALL, and R.L. GARCIA. Elevated CO_2 effects on stomatal density of wheat and sour orange trees. J. Exp. Bot. 45(280):1665-1668. WCL# 1874.

28. FLERCHINGER, G.N., M.S. MORAN, F.B. PIERSON, and G. FERNANDEZ. 1993. Chaos theory in hydrology. p. 101-111. IN: C.W. Richardson, A. Rango, L.B. Owens, and L.J. Lane (ed.), Proc. of the ARS Conf. on Hydrology, 1994-5, Denver, CO. 13-15 Sep 1993. WCL# 1766.

29. GARCIA, R.L., S.B. IDSO, G.W. WALL, and B.A. KIMBALL. 1994. Changes in net photosynthesis and growth of Pinus eldarica seedlings in response to atmospheric CO_2 enrichment. Plant, Cell and Environ. 17:971-978. WCL# 1713.

30. GARCIA, R.L., S.B. IDSO, and B.A. KIMBALL. Net photosynthesis as a function of carbon dioxide concentration in pine trees grown at ambient and elevated CO_2. Environ. & Exp. Bot. 4(3):337-341. WCL# 1714.

31. GRANT, R.F., B.A. KIMBALL, P.J. PINTER, JR., G.W. WALL, R.L. GARCIA, R.L. LAMORTE, and D.J. HUNSAKER. CO_2 effects on crop energy balance: Testing ecosys with a free-air CO_2 enrichment (FACE) experiment. Agronomy J. (ACCEPTED-DEC 1994). WCL# 1777.

32. HENDREY, G.R., and B.A. KIMBALL. 1994. The FACE Program. Agric. & Forest Meteorol. 70:3-14. WCL# 1684.

33. HENDRIX, D.L., J.R. MAUNEY, B.A. KIMBALL, K.F. LEWIN, J. NAGY, and G.R. HENDREY. Influence of elevated CO_2 and mild water stress on nonstructural carbohydrates in field-grown cotton tissues. Agric. & Forest Meteorol. 70:153-162. WCL# 1841.

34. HUMES, K.S., W.P. KUSTAS, and M.S. MORAN. 1994. Use of remote sensing and reference site measurements to estimate instantaneous surface energy balance components over a semi-arid rangeland watershed. Water Resource Res. 30:1363-1373. WCL# 1701.

35. HUMES, K.S., W.P. KUSTAS, M.S. MORAN, W.D. NICHOLS, and M.A. WELTZ. 1994. Variability in emissivity and surface temperature over a sparsely vegetated surface. Water Resource Res. 30:1299-1310. WCL# 1700.

36. HUNSAKER, D.J., G.R. HENDREY, B.A. KIMBALL, K.F. LEWIN, J.R. MAUNEY, and J. NAGY. 1994. Cotton evapotranspiration under field conditions with CO_2 enrichment and variable soil moisture regimes. Agric. & Forest Meteorol. 70:247-258. WCL# 1680.

37. HUNSAKER, D.J., and W.L. ALEXANDER. A lesquerella crop coefficient curve for computer-assisted irrigation scheduling in Arizona. IN: Proc. IX Int. Conf. on Jojoba & Its Uses and the III Int. Conf. on New Industrial Crops. (ACCEPTED-SEP 1994). WCL# 1817.

38. IDSO, K.E., and S.B. IDSO. 1994. Plant responses to atmospheric CO_2 enrichment in the face of environmental constraints: A review of the past ten years' research. Agric. & Forest Meteorol. 69:153-203. WCL# 1718.

39. IDSO, K.E., and S.B. IDSO. A synopsis of a major review of plant responses to rising levels of atmospheric carbon dioxide in the presence of unfavorable growing conditions. Am. Soc. of Agronomy Special Publication. (ACCEPTED-NOV 1994). WCL# 1808.

40. IDSO, K.E., and S.B. IDSO. The aerial fertilization effect of elevated CO_2 as modified by environmental limitations to plant growth. IN: Proc. Air and Waste Management Assoc. Int. Specialty Conf. on Global Climate Change. (ACCEPTED-APR 1994). WCL# 1802.

41. IDSO, S.B. 1994. Review of book, Assessing surprises and nonlinearities in greenhouse warming. IN: J. Darmstadter and M.A. Toman. J. of Natural Resources and Life Sciences Education. 23:154-155. WCL# 1787.

42. IDSO, S.B., K.E. IDSO, R.L. GARCIA, B.A. KIMBALL, and J.K. HOOBER. Effects of atmospheric CO_2 enrichment and foliar methanol application on net photosynthesis of sour orange tree (Citrus aurantium; rutaceae) leaves. Am. J. Bot. (ACCEPTED-JUL 1994). WCL# 1776.

43. IDSO, S.B., and B.A. KIMBALL. Carbon dioxide and sour orange trees: Results of the longest CO_2 enrichment experiment ever conducted. Proc. Air and Waste Management Association Int. Specialty Conf. on Global Climate Change. (ACCEPTED-APR 1994). WCL# 1801.

44. IDSO, S.B., and B.A. KIMBALL. 1994. Effects of atmospheric CO_2 enrichment on biomass accumulation and distribution in Eldarica pine trees. J. Exp. Bot. 45(280):1669-1672. WCL# 1711.

45. IDSO, S.B., and B.A. KIMBALL. 1994. Effects of atmospheric CO_2 enrichment on regrowth of sour orange trees (Citrus auranitium; rutaceae) after coppicing. Am. J. Bot. 81(7):843-846. WCL# 1739.

46. IDSO, S.B., and B.A. KIMBALL. 1994. Effects of atmospheric CO_2 enrichment on the growth of a desert succulent: Agave vilmoriniana Berger. J. of Arid. Environ. (ACCEPTED-MAR 1994). WCL# 1740.

47. IDSO, S.B., B.A. KIMBALL, G.W. WALL, R.L. GARCIA, R.L. LAMORTE, P.J. PINTER, JR., J.R. MAUNEY, G.R. HENDREY, K.F. LEWIN, and J. NAGY. 1994. Effects of free-air CO_2 enrichment on the light response curve of net photosynthesis in cotton leaves. Agric. & Forest Meteorol. 70:183-188. WCL# 1671.

48. IDSO, S.B. Long-term atmospheric CO_2 enrichment of trees. IN: Proc. Third Int. Workshop on Closed Ecological Systems. (ACCEPTED-OCT 1992). WCL# 1654.

49. INOUE, Y., M.S. MORAN, and P.J. PINTER, JR. 1994. Estimating potential and actual daily transpiration of crop canopies from remotely sensed spectral data and basic meteorological data -theory and initial test. p. 1061-1068. IN: Proc. 6th Int. Symp. Physical Measurements and Signatures in Remote Sensing, Val d'Isere, France. 17-21 Jan 1994. WCL# 1792.

50. INOUE, Y., M.S. MORAN, and P.J. PINTER, JR. 1994. Remote sensing of potential and actual daily transpiration of plant canopies based on spectral reflectance and infrared thermal measurements - concept with preliminary test. Japanese J. of Agric. Meteorol. 49:237-246. WCL# 1746.

51. INOUE, Y., and M.S. MORAN. 1994. A simplified mechanistic model for estimating potential and actual daily transpiration rates and crop water stress based on remotely sensed spectral and thermal data. Japanese J. Crop Sci. 63:81-82. WCL# 1835.

52. KIMBALL, B.A., R.L. LAMORTE, R.S. SEAY, P.J. PINTER, JR., R. ROKEY, D.J. HUNSAKER, W.A. DUGAS, M.L. HEUER, J.R. MAUNEY, G.R. HENDREY, K.F. LEWIN, and J. NAGY. 1994. Effects of free-air CO_2 enrichment on energy balance and evapotranspiration of cotton. Agric. & Forest Meteorol. 70:259-278. WCL# 1683.

53. KUSTAS, W.P., M.S. MORAN, K.S. HUMES, and C.C. TRUMAN. 1993. Remote sensing applications to hydrology. p. 67-80. IN: Proc. of the ARS Conf. on Hydrology, USDA, ARS 1994-5, Denver, CO. 13-15 Sep 1993. WCL# 1832.

54. KUSTAS, W.P., M.S. MORAN, K.S. HUMES, D.I. STANNARD, P.J. PINTER, JR., L.E. HIPPS, E. SWIATEK, and D.C. GOODRICH. 1994. Surface energy balance estimates at local and regional scales using optical remote sensing from an aircraft platform and atmospheric data collected over semiarid rangelands. Water Resources Res. 30:1241-1259. WCL# 1797.

55. KUSTAS, W.P., E.M. PERRY, P.C. DORAISWAMY, and M.S. MORAN. 1994. Using satellite remote sensing to extrapolate evapotranspiration estimates in time and space over a semiarid rangeland basin. Remote Sens. Environ. 49:275-286. WCL# 1765.

56. LEAVITT, S.W., E.A. PAUL, B.A. KIMBALL, G.R. HENDREY, J.R. MAUNEY, R.S. RAUSCHKOLB, H. ROGERS, K.F. LEWIN, J. Nagy, P.J. PINTER, JR., and H.B. JOHNSON. 1994. Carbon isotope dynamics of free-air CO_2-enriched cotton and soils. Agric. & Forest Meteorol. 70:87-101. WCL# 1758.

57. LECLERE, W.E., E. BAUTISTA, and S.A. RISH. 1994. 148 p. The Evaluation Report of the Demonstration Management Improvement Program in the Maricopa-Stanfield Irrigation and Drainage District. WCL# 1842.

58. LEWIN, K.F., G.R. HENDREY, J. NAGY, and R.L. LAMORTE. 1994. Design and application of a free-air carbon dioxide enrichment facility. Agric. & Forest Meteorol. 70:15-29. WCL# 1839.

59. MAUNEY, J.R., B.A. KIMBALL, P.J. PINTER, JR., R.L. LAMORTE, K.F. LEWIN, J. NAGY, and G.R. HENDREY. 1994. Growth and yield of cotton in response to a free-air carbon dioxide enrichment (FACE) environment. Agric. & Forest Meteorol. 70:49-67. WCL# 1759.

60. MORAN, M.S., S.J. MAAS, and P.J. PINTER, JR. Combining remote sensing and modeling for estimating surface evaporation and biomass production. Remote Sensing Reviews. (ACCEPTED-JUL 1994). WCL# 1719.

61. MORAN, M.S., T.R. CLARKE, Y. INOUE, and A. VIDAL. 1994. Estimating crop water deficit using the relation between surface-air temperature and spectral vegetation index. Remote Sensing of Environ. 49:246-263. WCL# 1735.

62. MORAN, M.S., T.R. CLARKE, W.P. KUSTAS, M.A. WELTZ, and S.A. AMER. 1994. Evaluation of hydrologic parameters in a semiarid rangeland using remotely sensed spectral data. Water Resour. Res. 30(5):1287-1297. WCL# 1665.

63. MORAN, M.S., D.C. GOODRICH, and W.P. KUSTAS. 1994. Integration of remote sensing and hydrologic modeling through multi-disciplinary semiarid field campaigns: Moonsoon '90, Walnut Gulch '92, and Salsa-Mex. p. 981-991. IN: Proc. 6th Int. Symp. Physical Measurements and Signatures in Remote Sensing, Val d'Isere, France. 17-21 Jan 1994. WCL# 1775.

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